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Spider diversity and the impact of ecologically dominant species on insect pests of rice and wheat crops

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Abstract

1. Spiders are an abundant and species-rich taxon of generalist predators that can affect herbivore populations and ecosystem functioning in agroecosystems. The present study was focused on the diversity and abundance of agroecosystem-inhabiting spiders and their impact on insect pests of rice and wheat crops. The crop fields were visited weekly to record spider diversity by the all-out search, sweep net and the pitfall trap methods.
2. Fourteen species of spiders and six species of insect herbivores were recorded in the rice and wheat cropping systems. The lynx spider, *Oxyopes javanus* and the web-making, *Neoscona theisi* and *Tetragnatha javana* were the ecologically dominant, arboreal species, while *Pardosa sumatrana*, an epigeal lycosid spider, was the dominant, ground-dwelling species, in both cropping systems.
3. Furthermore, to highlight the impact of these four ecologically dominant species of spiders on insect pests of crops, We propose estimates of the biomass of annually killed insect pests. In the event of an anticipated abundant prey availability, the annual prey kills of these four spider species were estimated to be in the range of ≈ 0.3-8 kg (fresh weight) over the entire cultivated field (Area= 65 ha).
4. The assessment of the estimated annual insect pests kill and the comparative impact of spider predation in the annual agroecosystems will help in expanding the approach of conservation biological control.

Key words Rice and wheat crops, Spider diversity, Insect pests, Annual insect pests kill, Biological control

Introduction

Arthropods exhibit outstanding diversity among the various animal taxa recorded on planet earth (Fenoglio *et al.*, 2020). The entomofaunal biodiversity of a region is often positively correlated with the plant diversity of that area (Joern & Laws, 2013). According to recent estimates, global species richness of arthropod is ≈ 14 million (Stork, 2018). This includes approximately 7 million species of terrestrial arthropods (Stork, 2018). The recent estimated global species richness of spiders includes 53,369 species belonging to 4,474 genera and 138 families worldwide (World Spider Catalog, 2025). Extremely high spider diversity has been recorded in the tropical countries, with 3,203 species belonging to 72 families reported from Brazil (Brescovit *et al.*, 2011), 501 species under 45 families, from Sri Lanka (Benjamin & Bambaradeniya, 2006) and 517 species belonging to 28 families reported from the Philippines (Barrion, 2001). From South Asia, a total of 2,299 species of spiders under 67 families have been reported (Siliwal *et al*., 2005), of which, 1,843 species belonging to 471 genera and 61 families have been reported from India, till date (Caleb & Sankaran, 2021).

Spiders are cosmopolitan and generalist predatory arthropods that consume variety of phytophagous insect pest while being harmless to the plants. Spiders exhibit a diversity of foraging characteristics and behaviour that promote biological control. Biological control through spiders is one of the best strategies to reduce the use of chemical pesticides as well as the population of the insect pests. Hence, long-term field investigations need to be conducted to elucidate the ecological roles of agroecosystem-inhabiting predatory arthropod species, such as spiders. Here, a good scientific approach would be to conduct field studies on those spider species which are abundant and ecologically dominant in the agroecosystems.

Rice and wheat are the most widely cultivated and consumed grain crops for nearly half of the world's population (Zeng *et al*., 2017). Both of these crops are India's basic cereal crops, commonly cultivated in Uttar Pradesh's Indo-Gangetic plains. These cereal crop plants are infested with a number of highly destructive insect herbivores (Ali *et al*., 2020). These include leaffolders, stem borers, gundhi bug, leafhoppers, grasshoppers etc. which are major pests of rice plants (Cabasan *et al*., 2019) while wheat aphids are the major pest of wheat plants (Yang *et al*., 2019). These insect pests collectively cause ≈ 25-30 percent yield loss (Bisen *et al*., 2019). Indiscriminate use of insecticides has extremely deleterious effect on the environment, exerts a negative effect on human health and non-targets such as pollinators and natural enemies of insect pests (Devine *et al*., 2007). This aspect also highlights the importance of maintaining agroecosystem biological diversity and predator-prey interactions as intact as possible in these artificial, highly simplified ecosystems (Fritz *et al*., 2011). It is therefore necessary to examine arthropod diversity of agroecosystems. In particular, field studies should be conducted to elucidate the ecological roles of beneficial arthropod species, such as generalist predators involved in suppression of insect pests, under natural field conditions.

The present study was designed to investigate the diversity and abundance of agroecosystem-inhabiting spiders and insect herbivores and to quantify the predation impact of ecologically dominant species on insect pests of rice and wheat crops. The field studies were conducted throughout the crop season (of rice and wheat crops), to study the diversity and abundance patterns of the potential generalist predators and the insect pests of crops at different stages of growth of the rice and wheat plants. The present study addressed two inter-related questions: (i) What are the diversity, abundance patterns and microhabitat preferences of spiders and their insect prey in rice and wheat agroecosystems? and (ii) What are the quantity annual insect pests kill by ecologically dominant species of spiders in the rice and wheat agroecosystems?

Materials and Methods

Study sites and system

The study was conducted during three crop seasons from June 2015 to April 2018 in field plots (n = 5, area = 200 m^2 in each case) located in the Agricultural farm in Banaras Hindu University campus, Varanasi in Uttar Pradesh, India. While the rice crop is cultivated from June to November, the period of cultivation of the wheat crop extends from December to April, each year, in this region (Mishra *et al*., 2021).

Rice cropping systems are subjected to frequent disturbances, including transplantation of rice seedlings, irrigation, use of chemical fertilizers, such as urea and di-ammonium phosphate (at the time of sowing the paddy seeds and again 21 days after transplantation) and use of herbicides, such as glyphosate (in the nursery). However, wheat cropping systems are subjected to relatively a smaller number of disturbances. These include irrigation (two or three times before the flowering period) and use of the same two chemical fertilizers.

Both rice and wheat crop plants have an average height of 60-120 cm. The conical inflorescence born on terminal shoots of rice plants is referred to as the panicle. However, the inflorescence of wheat is known as a spike, in which the spikelets are directly attached to the main axis (Ikeda *et al*., 2004). In the rice plants, flowering followed by fruiting begins during the month of September, each year. The reproductive phase of wheat plants begins during the month of February, each year.

Diversity and abundance of spiders and insect pests in cereal crops

Visual observation and pitfall trap collection methods were used for sampling the spiders and insect pests on rice (*Oryza sativa* Linnaeus) and wheat (*Triticum aestivum* Linnaeus) crops in five randomly selected field plots (size per plot = 200 m^2 area) (Mishra *et al*., 2021). Spider diversity and abundance were also recorded in the fallow fields, (following harvesting of wheat crop) by visual observation and the pitfall trap (n = 15 traps/plot; 5 rows/field; i.e. 75 traps/field) collection methods.

The diversity and abundance of agroecosystem-inhabiting species of insect pests of wheat crop were recorded similarly by the visual observation and the pitfall trap methods, in the fallow and cultivated field plots. Since the data obtained for the diversity and abundance of spiders for each of the three seasons (for each crop) showed a similar pattern, hence it was pooled, in each case.

Microhabitat preferences of spiders and insect pests

The microhabitat preferences of the various species of rice and wheat agroecosystem-inhabiting spiders on the crop plant parts and/or on the ground were also recorded by visual observation method.

Standing biomass of crop field-inhabiting ecologically dominant species of spiders

Biomass (fresh weight in mg) of each of the four ecologically dominant species of spider was taken in different quadrats (n=100) in randomly selected crop fields. Further to calculate the standing biomass (mg m^{-2}) of each of the four species of spider in annual agroecosystem, the obtained mean biomasses of each spider were multiplied by entire area (65 ha) of cultivated field.

Estimate of the annual insect pests kill by the ecologically dominant species of spiders

The estimate is based on the spiders' per day food requirements per unit body weight, as assessed in an earlier finding (Mishra *et al*., 2021) in combination with spider biomass m^{-2} values. Based on the spider biomass m^{-2} values from Table 1 and the evaluated average daily prey intake (mg day^{-1}), the prey kill m^{-2} day^{-1} of each of the four spider species in rice and wheat cropping systems were assessed. The obtained values were further converted in to prey kill m^{-2} $year^{-1}$ for each cropping system, considering the duration of prey availability was only for 5 months in each crop, in 30 -150 days old rice and wheat plants. The resulting values were then used to derive the total prey kill in each cropping system, by multiplying outcomes (prey kill in m^{-2} $year^{-1}$) with the total cultivated area (65 ha). Since, the variation in per day prey intake among rice and wheat field-inhabiting spiders is considered to be very low, hence it has been neglected. Therefore, by summing the subtotals of both cropping systems, an estimated annual prey kill of crop field inhabiting spiders were determined.

Data analyses

The data obtained in the study was checked for normal distribution using Shapiro - Wilk test for normality and Bartlett's test for homogeneity of variances prior to subjecting it to further analysis. An analysis of variance (one-way ANOVA) followed by Tukey's *post-hoc* test was applied to analyze the variations in the diversity of spider per quadrat and also to analyze the variations in the abundance of spiders collected by the pitfall traps method. The variations in the insect pest diversity were also subjected to one way ANOVA followed by Tukey's *post hoc* comparison of means.

Results

Diversity and abundance of spiders and insect pests:

i. Rice cropping system

Twelve species of spiders were recorded in the rice cropping system, by the visual scanning and the pitfall trap collection methods (Table 1; Fig. 2).

A total of five insect pests of rice, including the rice green leafhopper, *Nephotettix nigropictus* Matsumura (Hemiptera: Cicadellidae); the rice bug, *Leptocorisa varicornis* Fabricius (Hemiptera: Alydidae); the rice leaffolder, *Cnaphalocrosis medinalis* Guenée (Lepidoptera: Crambidae); the yellow stem borer, *Scirpophaga incertulas* Walker (Lepidoptera: Crambidae) and the rice grasshopper, *Oxya nitidula* Walker (Orthoptera: Acrididae) were recorded by the visual scan method (Table 2). However, only nymphs of grasshopper, nymphs and adults of rice bug, adults of leafhopper, leaffolder and stem borer were recorded in the traps of web-making species of spiders. The abundance of insect pests varied significantly (One-way ANOVA: $F_{4,120} = 4.670$, $P < 0.01$). The abundance of insect pests was found to be highest during October (Fig. 4). *O. nitidula* was found to be present during all the growth stages of rice plants.

ii. Wheat cropping system

A total of ten species of spiders belonging to seven genera and four families were recorded in the wheat agroecosystem, by the visual scan and the pitfall trap collection methods. The abundance of spider species varied significantly (One-way ANOVA: $F_{9,490} = 20.722$, $P < 0.001$) with the arboreal hunter *Oxyopes javanus* and weaver, *Neoscona theisi* having a higher abundance (Tukey's *post hoc* test: $P < 0.001$) as compared to the co-existing species (Fig. 1). *Tetragnatha javana*, a web-making spider, was also prevalent, though to a lesser extent than the co-existing species. In comparison to the other co-existing species, the ground-dwelling hunting lycosid spider, *Pardosa sumatrana* (Tukey's *post ho*c test: $P < 0.001$), exhibited a higher abundance in the trap collections (Fig. 1 & 2).

Three species of insect pests: the wheat aphid, *Sitobion avenae* Fabricius (*Hemiptera*: Aphididae)*,* the grasshopper, *O. nitidula* and the cotton bollworm, *Helicoverpa armigera* Hübner (Lepidoptera) were recorded in the wheat agroecosystem. The abundance of insect pests varied significantly (One-way ANOVA: $F_{2,72} = 8.461$, $P < 0.001$). However, the abundance of *S. avenae* was found to be highest as compared to other species of wheat crop insect pests (Fig. 3).

Microhabitat preferences of spiders and insect pests

i. Spiders

Web-weaving spiders (*Leucauge decorata*, *N. theisi*, *T. javana*, *Argiope bruennichi* and *Hippasa greenalliae*), and the hunting spiders (*O. javanus, O. elongates O. shweta, Plexippus paykulli, Hyllus semicupreus* and *Thomisus spectabilis*) were recorded from the foliage, stem and rice plant panicles and also on the spikelets of wheat plant, while the wolf spiders, *P. sumatrana*, *P. birmanica* and *P. shyamae* were recorded mainly on the soil surface although these three epigeal species were occasionally also recorded on the basal parts of the crop plants (Table 1).

Table 1. Abundance, microhabitat preferences and feeding guilds of spiders in wheat and rice agroecosystems.

Spider species	**Abundance/quadrat**		**Guild**	**Microhabitat**	**Category**
	Rice	**Wheat**			
Leucauge decorata	0.66±0.13	0.60±0.14	Orb weaver	Leaf/Panicle/Spikelet	Arboreal web
Neoscona theisi	2.26±0.29	2.30±0.19	Orb Weaver	Stem/Leaf	Arboreal web
Tetragnatha javana	0.94±0.17	1.82±0.17	Orb weaver	Stem/Leaf	Arboreal web
Argiope bruennichi	0.22±0.06	-	Orb weaver	Leaf	Arboreal web
Hippasa greenalliae	0.34±0.06	0.94±0.13	Tunnel weaver	Leaf	Ground web
Oxyopes javanus	1.52±0.12	1.55±0.13	Stalker	Leaf/Panicle/Spikelet	Arboreal hunter
Oxyopes elongatus	-	0.74±0.09	Stalker	Leaf/Spikelet	Arboreal hunter
Oxyopes shweta	0.49±0.06	-	Stalker	Leaf/Panicle	Arboreal hunter
Pardosa sumatrana	2.90±0.37	2.68±0.17	Ground dweller	Ground	Epigeal hunter
Pardosa birmanica	1.84±0.27	0.95±0.10	Ground dweller	Ground	Epigeal hunter
Pardosa shyamae	-	0.61±0.08	Ground dweller	Ground	Epigeal hunter
Hyllus semicupreus	1.12±0.15	1.23±0.10	Jumping spider	Ground	Epigeal hunter
Plexippus paykulli	0.24±0.04	-	Jumping spider	Leaf	Arboreal hunter
Thomisus spectabilis	0.14±0.05	-	Wanderer	Stem/Leaf/ Spikelet	Arboreal hunter

ii. Insect pests

The phytophagous insect pests (*S. incertulas, C. medinalis, H. armigera, N. nigropictus* and *O. nitidula*), were recorded predominantly on the crop foliage. While the bug, *L. varicornis* was recorded exclusively on the rice plant panicles, the wheat aphid, *S. avenae* occurred predominantly on the wheat spikelets (Table 2).

Table 2. Abundance, microhabitat preferences and feeding guilds of insect herbivores in wheat and rice agroecosystems.

Insect pest Species	**Abundance/quadrat**		**Microhabitat**	**Damage causing stage**	**Type of pest**
	Rice	**Wheat**			
Scirpophaga incertulas	0.80±0.21	-	Leaf	Caterpillar	Stem borer
Cnaphalocrocis medinalis	3.26±0.90	-	Leaf	Caterpillar	Leaffolder
Helicoverpa armigera	-	1.48±0.31	Leaf/Spikelet	Caterpillar	Defoliator
Sitobion avenae	-	39.36±8.77	Leaf/Spikelet	Nymph	Sap sucker
Leptocorisa varicornis	4.63±1.11	-	Leaf/Panicle	Nymph/adult	Grain/Pod sucker
Nephotettix nigropictus	1.73±0.36	-	Leaf	Nymph/adult	Sap sucker
Oxya nitidula	2.7±0.58	4.12±0.41	Leaf	Nymph/adult	Defoliator

Table 3. Estimated standing biomass of the four ecologically dominant species of spiders.

Spider species	**Mean Biomass (mg m^{-2}) (B)**	**Area in m^2 (A)**	**Biomass subtotal (g) (B×A)**
Oxyopes javanus	10.92	65×10^4	7103.72
Pardosa sumatrana	18.21		11837.80
Tetragnatha javana	7.23		4704.70
Neoscona theisi	45.76		29747.25
Total standing biomass of spiders			53393.47

Table 4. Estimated annual prey kill by four ecologically dominant species of rice field-inhabiting spiders (expressed as fresh weight in mg day^{-1}).

Spider species	**Abundance (m^{-2}) (A)**	**Insect pests**	**Prey biomass (mg day^{-1}) (B)**	**Prey killed (mg m^{-2} day^{-1}) (A×B)**	**Prey killed (mg m^{-2} year^{-1}) (A×B×365)**
Oxyopes javanus	1.52±0.12	*Nephotettix nigropictus*	22.10±1.96	33.59	12260.35
		Cnaphalocrocis medinalis	9.16±0.10	13.92	5080.80
		Scirpophaga incertulas	7.35±0.22	11.17	4077.05
		Leptocorisa varicornis	16.70±1.96	25.38	9263.70
		Oxya nitidula	4.41±0.27	6.70	2445.50
		Total			**33127.40**
Pardosa sumatrana	2.90±0.37	*Nephotettix nigropictus*	2.18±0.19	6.32	2306.80
		Cnaphalocrocis medinalis	3.01±0.31	8.72	3182.80
		Scirpophaga incertulas	1.95±0.12	5.65	2062.25
		Leptocorisa varicornis	6.80±1.52	19.72	7197.80
		Oxya nitidula	5.00±0.00	14.5	5292.50
		Total			**20042.15**
Tetragnatha javana	0.94±0.17	*Nephotettix nigropictus*	5.36±0.63	5.03	1835.95
		Cnaphalocrocis medinalis	14.32±0.62	13.46	4912.90
		Scirpophaga incertulas	11.27±0.50	10.59	3865.35
		Leptocorisa varicornis	11.85±1.79	11.13	4062.45
		Oxya nitidula	5.00±0.00	4.70	1715.50
		Total			**16392.15**
Neoscona theisi	2.26±0.29	*Nephotettix nigropictus*	6.66±0.45	15.05	5493.25
		Cnaphalocrocis medinalis	10.09±0.40	22.80	8322.00
		Scirpophaga incertulas	9.20±0.35	20.79	7588.35
		Leptocorisa varicornis	10.74±0.53	24.27	8858.55
		Oxya nitidula	16.41±1.13	37.08	13534.2
		Total			**43796.35**
	Estimated prey killed by the spiders/year				**113358.05**

Table 5. Estimated annual prey kill by four ecologically dominant species of wheat field-inhabiting spiders (expressed as fresh weight mg day^{-1}).

Spider species	Abundance **(m^{-2})** (A)	***Sitobion avenae***	Prey biomass* **(mg day^{-1})** (B)	Prey killed **(mg m^{-2} day^{-1})** (A×B)	Prey killed **(mg m^{-2} year^{-1})** (A×B×365)
Oxyopes javanus	1.55±0.13	Wingless	1.71±0.32	2.65	967.25
		Winged	0.86±0.15	1.33	485.45
		Total			**1452.70**

Pardosa sumatrana	2.68±0.17	Wingless	0.58±0.08	1.55	565.75
		Winged	0.43±0.09	1.15	419.75
		Total			**985.50**
Tetragnatha javana	1.82±0.17	Wingless	0.67±0.09	1.21	441.65
		Winged	0.58±0.09	1.05	383.25
		Total			**824.90**
Neoscona theisi	2.30±0.19	Wingless	2.03±0.21	4.66	1700.90
		Winged	0.92±0.13	2.11	772.34
		Total			**2473.24**
	Estimated prey killed by the spiders/year				**5736.34**

*In Laboratory based experimental condition

Table 6. Estimated annual prey kill by the four ecologically dominant species of rice and wheat field inhabiting spiders (expressed as fresh weight g year^{-1}).

Agroecosystem	Number of replicates	Total prey kill (g m^{-2} year^{-1})	Area in m^2	Prey kill of entire area (g m^{-2} year^{-1})
Rice	10	113	65×10^4	7345×10^4
Wheat	10	6		390×10^4

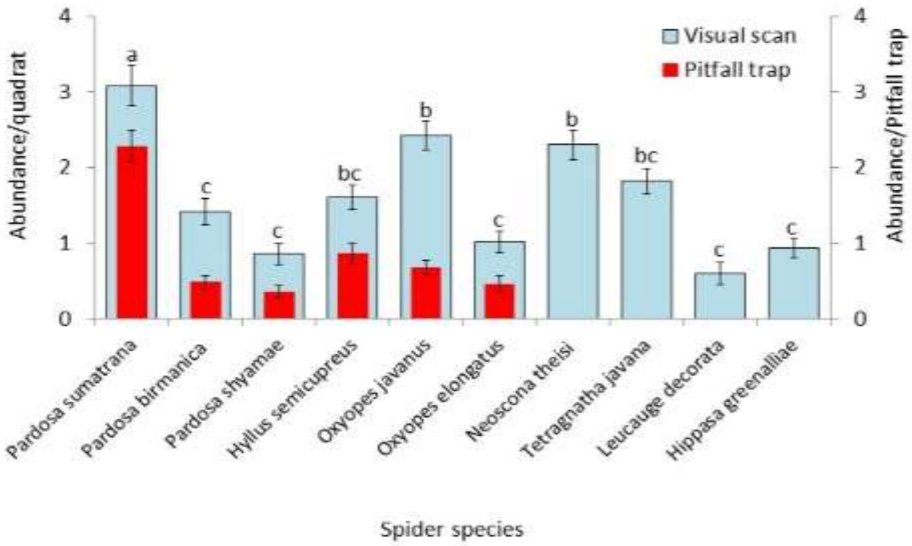

Figure 1. Spider diversity and abundance recorded in the wheat agroecosystem located in the Agricultural farm of Banaras Hindu University, Varanasi, India (June, 2015 – April, 2018). Means within a panel capped with different letters are significantly different. One-way ANOVA followed by Tukey's *post-hoc* test: $P < 0.05$.

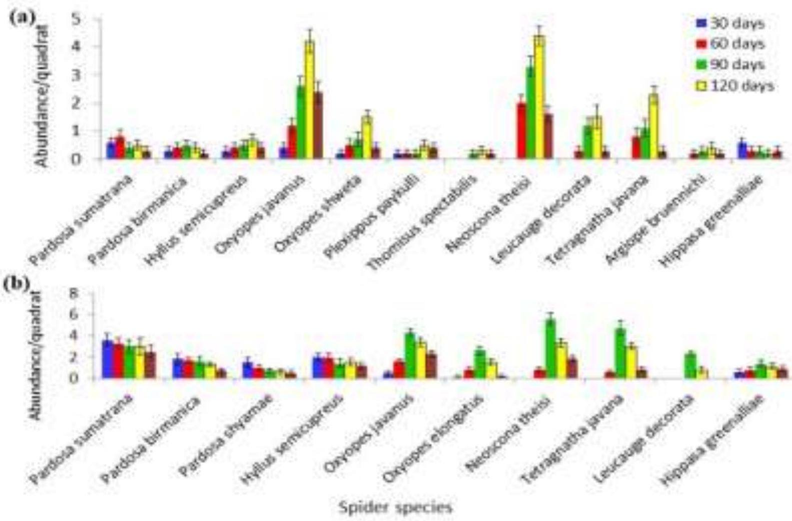

Figure 2. Seasonal occurrence patterns of wheat crop-inhabiting spiders, on 30–150 day old plants located in the Agricultural farm of Banaras Hindu University, Varanasi, India (June, 2015 – April, 2018). One-way ANOVA followed by Tukey's *post-hoc* test: $P < 0.05$.

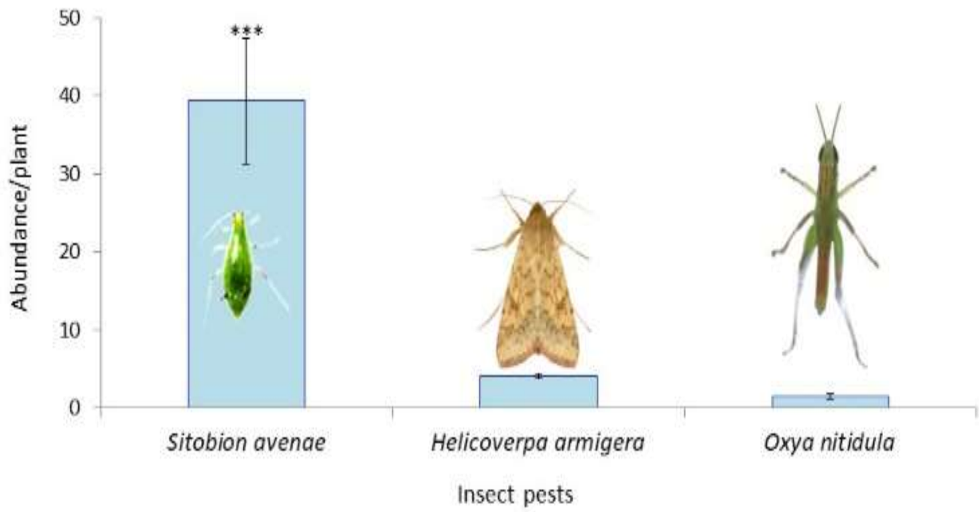

Figure 3. Insect pest diversity and abundance in: (a) rice and (b) wheat agroecosystems located in the Agricultural farm of Banaras Hindu University, Varanasi, India (June, 2015 – April, 2018). One-way ANOVA followed by Tukey's *post-hoc* test: $^{***}P < 0.001$.

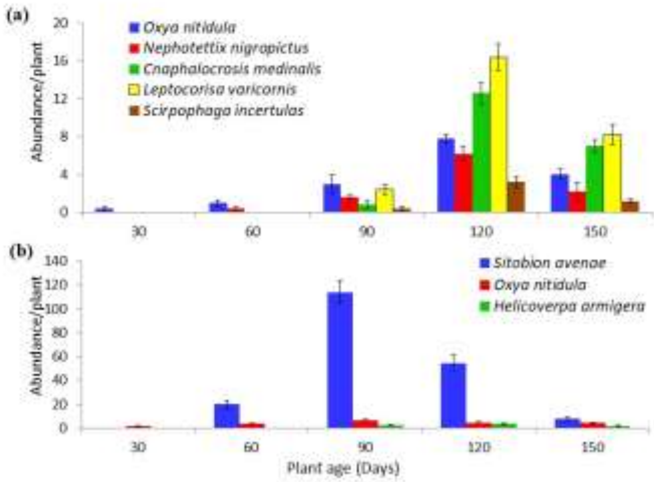

Figure 4. Seasonal occurrence patterns of insect herbivores in: (a) rice and (b) wheat agroecosystems on 30-150 day-old plants, located in the Agricultural farm of Banaras Hindu University, Varanasi, India (June, 2015 – April, 2018). One-way ANOVA followed by Tukey's *post-hoc* test: $P < 0.05$.

Standing biomass and estimated annual insect pests kill by crop field-inhabiting ecologically dominant species of spiders

Assessment based on estimates of average spider biomass m^{-2} in rice and wheat agroecosystems revealed that the overall standing biomass of the four ecologically dominant spider species were 53.39×10^3 g (≈ 53 Kg fresh weight; Table 3 & 4). The biomass m^{-2} was highest in case of *N. theisi* in both rice and wheat agroecosystems and the biomass showed the following trend in the decreasing order: *N. theisi* > *P. sumatrana* > *O. javanus* > *T. javana*. The annual insect pests kill by these four spider species was estimated to be in the range of 0.3-7.34 kg $year^{-1}$ (≈ 8 kg $year^{-1}$; Table 5).

Discussion

Our presumptions led to a significant contribution of the spiders in the suppression of insect pests of crops with estimated annual prey kill in the range of ≈ 0.3-8 kg (fresh weight) over the entire cultivated field (Area= 65 ha) of rice and wheat crops (Table 5). Earlier studies have also shown that spiders can reduce the population of insect herbivores by 1-20% in an annual cropping system (Sunderland *et al*., 1986; Nyffeler & Birkhofer, 2017). The phytophagous pest guild of cereal crops was represented and dominated by sap feeding hemipteran, as well as by the foliage feeding (the damaging stages with biting and chewing mouth parts) lepidopteran and orthopteran pest species (Fig. 3). Moreover, the insect pests belonging to these orders were the preferred prey for all the species of rice and wheat field spiders (Mishra *et al*., 2021). The use of spiders in conservation biological control of insect pests of crops has enormous potential in insect pest management since recent studies also emphasize the outstanding role of spiders among generalist predators (Nyffeler & Birkhofer, 2017).

A total of 14 species of spiders were recorded from the rice and wheat cropping systems (Table 1). While the three spider species, *L. decorata,* H. *greenalliae* and *A. bruennichi,* were late colonisers, the abundance of the latter two was consistently low during the entire crop growing season (Fig. 2). These three appear to be temperature-sensitive spider species. It is plausible that *A. bruennichi,* which was recorded only in the rice cropping systems and was consistently absent in the wheat agroecosystem, is adapted to a narrow range of temperature and humidity. The present study supports earlier findings which reveal that during the last 100 years, *A. bruennichi* has gradually shifted its range northwards, in Europe, (Krehenwinkel & Tautz, 2013). The lynx spider, *O. javanus* and web-weavers, *N. theisi*, and *T. javana* were not only early colonisers but also their population build-up was rapid during the flowering and grain forming stages of the crop plant. In contrast, the abundance of the arboreal, *O. elongates*, *O. shweta, P. paykulli* and *T. spectabilis* and of the epigeal, *P. birmanica*, *P. shyamae* and *H. semicupreus,* was consistently low, during the entire crop growing season. The results of present study reveal that the lynx spider, *O. javanus,* the web-weaving, *N. theisi* and *T. javana,* were the three most abundant arboreal species while the hunting lycosid spider, *P. sumatrana,* was the most abundant ground-dwelling spider species, in both rice and wheat agroecosystems. These four species of spiders appear to be the most ecologically dominant species, in cereal agroecosystems. These findings provide support for previous studies indicating that the members of Lycosidae, Araneidae, Oxyopidae, Salticidae and Tetragnathidae, are found to be widespread in tropical annual agroecosystems (Bao *et al*., 2018). Members of Araneidae and Oxyopidae have been shown to be one of the most widespread and dominant families in many annual agroecosystems of the world (Namkung *et al*., 2000) including the rice agroecosystems of tropical countries, such as China (Barrion *et al*., 2012), Brazil (Rodrigues *et al*., 2009) and India (Kumari *et al*., 2017). They are also reported from perennial agroecosystems, for instance, Olive (Cárdenas *et al*., 2006) and Guava (Mishra & Rastogi, 2020) orchards. Moreover, in some rice-growing countries, members of the Lycosidae and Tetragnathidae families are the most common spiders (Bao *et al*., 2018).

A total of five species of insect herbivores were recorded in the rice agroecosystem (Table 2). The abundance of all the five herbivore species increased during the flowering season and reached the peak values during the grain-forming stage of the crop plants (Fig. 4). The abundance per plant was highest in case of *L. varicornis* and the abundance pattern showed the following trend in the decreasing order: *L. varicornis* > *C. medinalis* > *O. nitidula* > *N. nigropictus* > *S. incertulas*. While *L. varicornis* and *O. nitidula* showed higher preference for the grain bearing part of the panicle, the rice leaffolder, *C. medinalis* and the yellow stem borer, *S. incertulas* were found mainly on the foliage. The rice green hopper, *N. nigropictus* was recorded on both the foliage as well as the panicle.

A total of three insect herbivore species were recorded from the wheat agroecosystem (Fig. 3). The abundance of *S. avenae* was highest followed by *H. armigera* and *O. nitidula.* The wheat aphid, *S. avenae* and the army worm, *H. armigera* were found predominantly on the spikelets and to a lesser extent on the crop plant foliage. The grasshopper, *O. nitidula* was present mainly on the plant foliage (Table 2).

The phytophagous pest guild of cereal crops was represented and dominated by sap feeding hemipteran, as well as by the foliage feeding (the damaging stages with biting and chewing mouth parts) lepidopteran and orthopteran pest species.

The results revealed well-marked spatial and temporal patterns in the diversity and abundance patterns of the spider communities, in each of the two cropping systems. The spider assemblages of rice and wheat fields showed high diversity with only minor differences in the composition and abundance patterns. The diversity was particularly high among the arboreal species of spiders.

The diversity and abundance of spiders in crop fields is documented to be affected by many biotic and abiotic factors, including spider movement, reproduction, and number of web-making and wandering spiders, density and distributions of target insect prey, variation among habitats and agronomical practices and the extent of inter-guild competition (Wang *et al*., 2002).

The abundance of spiders and the insect pests in each field was lower during the vegetative stages and gradually increased till the beginning of the grain-forming stages of the two types of crops. Recently sown fields are typically characterized by low vegetation and the time during this stage represents a critical period for colonisation and establishment of arthropod predators (Ryptstra *et al*., 1999). The recovery of spider populations after disturbances in the field is achieved by reproduction, but immigration from surrounding habitats is also very important (Thorbek & Topping, 2005). As a consequence, surrounding habitats such as pastures, other crops, and riparian vegetation patches can serve as spider reservoirs, allowing spider species to recolonise crop fields after temporary agronomical practice related disturbances (Thorbek & Bilde, 2004).

Absence of web-supporting structures may also be important in influencing the web-making spider assemblage of a place. In the present study, web-building spiders were found to be abundant during the crop flowering and grain-forming periods but their abundance dramatically decreased during the fallow period. After the crop was harvested there was a complete lack of vegetation to serve as a suitable substrate for web construction and the abundance of web-making species of spiders in the field was severely affected.

Spiders have been observed in various strata of crop plants and weeds, as well as on the ground surface. Many spider species are efficient predators of insect herbivores (Mishra *et al.*, 2022). The colonisation and succession patterns of spiders and insect pests in the wheat field habitats was found to follow a uniform pattern in relation to the growth stages of the crop as well as the different phases of the rice and wheat fields (Mishra & Rastogi, 2023). Wolf spiders were among the most dominant ground-dwelling arthropods in wheat agroecosystems. It is known that many species of wolf spiders (particularly those belonging to the genus *Pardosa*) can rapidly colonise disturbance-driven agroecosystems. The early colonisation and build-up of spider communities recorded in the wheat field in the present study, supports earlier findings (Bambaradeniya & Edirisinghe, 2009), which reported that the ground-dwelling wolf spiders colonised faster than other coexisting species. The numerical dominance of spiders during the flowering and grain-forming stages of the crops can be attributed to an increase in the availability of microhabitats in relation to the architecture of the crop plants. This increase is presumably also linked to the increase in the availability and abundance of their potential insect prey. The grain ripening stages of the crop plants probably provide innumerable niches for the insect herbivores and also their spider predators. Field irrigation and draining phases, during the crop-growing season may also have created new habitats by exposing the soil surface for spiders, to colonise. However, harvesting of the crop plants results in population reduction of the spiders due to the loss of vegetation and the consequent drastic reduction in the insect herbivores. Thus, the results of this part of the study highlight the diversity, abundance and seasonal variations of the spider fauna associated with the rice and wheat crops in agricultural fields. The changes in the arthropod communities in the rice and wheat fields appear to be largely governed by ecological changes that are imposed in the rice ecosystem as a consequence of the cultivation practices essential to rice cultivation.

Conclusions

The annual cropping systems were characterized by a high diversity and abundance of hunting and web-making spiders. The lynx spider, *O. javanus* and the web-making, *N. theisi* and *T. javana* were the ecologically dominant, arboreal species, while *P. sumatrana*, an epigeal lycosid spider, was the dominant, ground-dwelling species, in both rice and wheat agroecosystems. The four ecologically dominant spider species were not only early colonisers of crop fields but also showed a rapid population build-up during the flowering and grain-forming stages of the crops.

The estimated standing biomass of these spiders was found to be very high (≈ 54 Kg, Table 5) in the cultivated crop fields. They consumed a large number insect pest of rice and wheat crops. These findings highlight the outstanding potential of spider assemblages on economically important insect herbivores in the agroecosystem.

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Authors' contributions

Both authors conceived the ideas and designed the methodology. A.M. conducted experiments, analyzed data and wrote the manuscript. Both authors read and approved the manuscript. N.R. supervised A.M. as a part of his PhD education and contributed critically to the drafts and gave final approval for publication.

Conflict of interest

The authors declare no conflict of interest.

Data availability statement

The datasets generated and analysed during the current study are available from the corresponding author on request.

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