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Review

Mosquito management strategies in European rice fields: Environmental and public health perspectives

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ABSTRACT

Rice is a crucial food source and an important economic activity globally. Rice fields provide habitats for birds and other organisms but also serve as ideal breeding grounds for mosquitoes, including potential vectors such as *Culex*, *Aedes*, and *Anopheles*. There is an urgent need to manage mosquitoes associated with rice crops, as they are important pests and vectors of diverse pathogens. Effective management should rely on cost-effective, legislative, and environmentally sustainable approaches. We gathered information from various sources on surveillance, phenology, mosquito nuisance, vector-borne diseases and control measures in the main rice paddies of the five major rice-producing regions in Europe: Italy, Spain, Greece, Portugal, and France. Mosquito problems in rice paddies are prevalent across most analyzed regions, with entomological and virological surveillance efforts varying in intensity and timing. *Aedes caspius* mosquitoes significantly contribute to nuisance levels, while recent West Nile virus (WNV) circulation poses the most serious threat, as these habitats support high densities of mosquito vectors such as *Culex pipiens*, *Culex modestus*, and *Culex perexiguus*. Different mosquito control strategies are applied, ranging from centralized programs to localized interventions funded by public entities and implemented by public or private companies. Biological larviciding with *Bacillus thuringiensis* serovar. *israelensis* is the primary method used, supplemented by adulticiding during epidemic outbreaks in nearby urban areas. These management approaches reflect diverse regional contexts and highlight the importance of adaptive strategies in addressing mosquito-related challenges across rice paddies in Europe.

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1. Introduction

Rice has been cultivated in Europe for many centuries, but large-scale production began in the early twentieth century. In 2015, ca. half a million hectares of land were cultivated with rice in the European Union. Although this figure is small compared to other crops, rice is considered an important agricultural commodity in Europe, with significant economic value (Chauhan et al., 2017; Kraehmer et al., 2017; Muthayya et al., 2014). Furthermore, rice fields are known to provide important ecosystem services as substitutes of natural wetlands (Natuhara, 2013), and serve as crucial habitats for a wide variety of organisms that would not survive in non-irrigated environments. There is also evidence that rice-field ecosystems play a major role as refuges for water birds (Toral and Figuerola, 2010).

Several countries in the European Union cultivate rice, including Italy, Spain, Greece, Portugal, France, Romania, Bulgaria, and Hungary (FAO, 2022). Major rice-growing regions include the Po valley in Italy, the Ebro Delta and Guadalquivir valley in Spain, the western agricultural area of Thessaloniki in Greece, the Rhone delta region in France, and the Tejo and Mondego valleys in Portugal. All rice fields in Europe are irrigated with intermittent cycles of drying and flooding, creating ideal environments for the development of a wide variety of mosquito species. This often leads to high levels of mosquito nuisance to surrounding communities. In fact, residents and visitors near these environments have reported unbearable mosquito nuisance throughout the spring and summer seasons, with instances of 150–200 mosquito bites in just a few minutes if adequate personal protection measures are not adopted (Chaskopoulou et al., 2011a; Piakis et al., 2007). Furthermore, the emergence and re-emergence of mosquito-borne diseases, such as West Nile virus (WNV) and Usutu virus, in recent decades in Europe is often associated with flooded areas including natural wetlands and rice fields. This has led to increased local interest in mosquito surveillance and control in these environments (Kovach and Kilpatrick, 2018; Pradier et al., 2014; Roiz et al., 2014). The presence of irrigated croplands has been identified as a major factor positively associated with WNV human cases across North America and Europe (Marcantonio et al., 2015; Kovach and Kilpatrick, 2024). Recent analyses have concluded that rice cultivation is positively associated with a higher incidence of WNV cases in human and horse in Europe (García San Miguel et al., 2021; García-Carrasco et al., 2023). One of the most notable WNV outbreaks in Europe, characterized by unusually high severity, occurred in 2010 in a major urban area (Thessaloniki, Greece) (Koch et al., 2024). This location was near extensive river plains and agricultural regions dominated by rice cultivation. The presence of large populations of native and migrant birds, which can act as virus reservoirs (Toral and Figuerola, 2010), coupled with abundant mosquito vectors, likely facilitated the amplification of the virus and its eventual transmission to nearby urban environments (Chaskopoulou et al., 2013), and the recurrence of human cases in that area since 2010 (Angelou et al., 2024). Similar outbreaks have occurred at some of the major rice-growing areas in Spain (García San Miguel et al., 2021) and France (Leblond et al., 2007).

Most of the available data, knowledge, and experience on mosquito control in rice-field dominated areas come from the United States, Africa, and South Asia (Chan et al., 2022; Wheeler et al., 2022; Zhao and Xue, 2022). These regions employ various vector management practices with differing levels of efficacy. However, there is limited information on practices used in Europe (Bellini et al., 2014), likely due to the historically low impact of vector-borne diseases (VBDs) in these environments. Although surveillance and vector control programs have been implemented in some European rice production areas, there is limited common knowledge regarding the impact and sustainability of these interventions (ECDC, 2014). A recent survey aimed at appraising the challenges on WNV management in various European contexts concluded that the efficacy and sustainability of vector control operations in natural wetlands and rice fields are particularly difficult due to the high vector abundance in these vulnerable and complex environments. The primary reasons were the lack of cost-effective biocides and a complicated regulatory framework that fails to address the unique challenges of these environments (ECDC, 2020). The high sensitivity of non-target aquatic species to many biocides, coupled with the proximity of rice fields to natural wetlands and often to urban areas, creates an scenario where balancing biodiversity, ecosystem services, and public health requirements may be difficult to achieve (Martinou et al., 2020).

In an effort to raise awareness on the challenges of VBD management in intensive rice agroecosystems and identify specific knowledge gaps, we compiled the most up-to date information on mosquito surveillance, nuisance, and mosquito control approaches used in the five major rice cultivation countries of Europe: Italy, Spain, Greece, Portugal, and France.

2. Material and methods

Given the multiple rice-cultivation regions per country, this review primarily focuses on the 14 major zones. Information was gathered through a literature review, but mainly through unpublished reports and data provided by local authorities, farmers, and natural park managers that were directly inquired for the mosquito control strategies at each of these areas and for supporting documentation when available. Most of the information for Europe is not easily available (i.e. grey literature and conference proceedings, often in non-English languages), so country-based researchers with expertise in mosquito ecology participated in this study to facilitate access to the most relevant published and grey literature information available. This study is not a systematic literature review but offers critical references of major interest. Our study focuses exclusively on rice fields, as information on other waterlogged habitats has been published elsewhere. We have limited references to other habitats, only mentioning urban areas surrounding the target habitats where necessary. The review includes information from the 21st century, particularly from the last 10 years. If no such information is available, data from earlier years is used (especially in cases involving fauna information).

A graphical summary providing a visual representation of the research can be found in Fig. 1. All information is presented below in five main sections, subdivided by country. Additionally, a detailed summary of all data related to surveillance, trapping methods, main mosquito species, VBD/nuisance issues is provided in Tables 1 and 2.

3. Results

3.1. Rice field cultivation per country

Italy: Currently, around 240,000 ha are devoted for growing rice, representing ca. 60% of the entire European Union rice crop (Arcieri and Ghinassi, 2020). Rice cultivation in Italy is primarily concentrated in the north, mostly in the flat plains of Po Valley, particularly in the regions of Piedmont and Lombardy (both accounting for over 90%), but also in Emilia-Romagna and Veneto (ca. 6%) (Table 1). Small areas (less than 4%) are cropped in Sardinia and southern Italy as well (Sibari Plain) (Arcieri and Ghinassi, 2020) (Table 1, Fig. 2).

Spain: Spain is the second largest rice-producing country in the European Union, with ca. 105,000 ha (30% of the total European rice production). The major rice-producing regions are Andalusia, Extremadura, Catalonia, and Valencia accounting for over 96% of the production (De Barreda et al., 2021) (Table 1, Fig. 2).

Greece: Rice-cultivation is primarily concentrated in Northern Greece, in the Regions of Central Macedonia and Eastern Macedonia and Thrace, with Thessaloniki and Kavala Regional Units hosting some of the largest cultivation areas. Approximately 27,700 ha of rice fields are cultivated between both areas, with slight fluctuations (HSA, 2021). Both Thessaloniki and Kavala rice-agroecosystems are near natural wetlands, including the extensive river deltas of the Axios, Loudias,

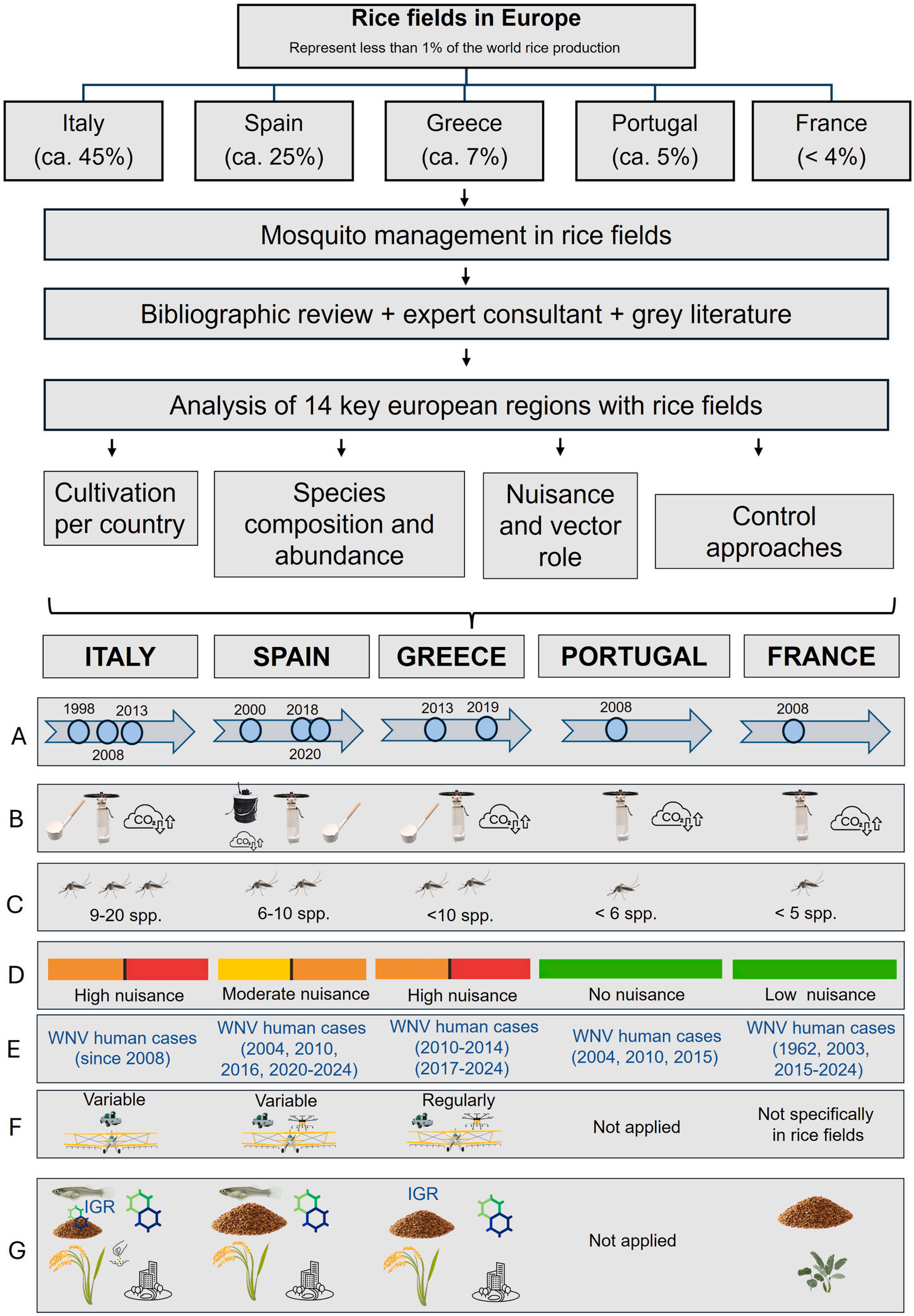

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Fig. 1. Graphical summary providing an overview of the analysis conducted in the five main rice-producing countries in Europe. (**A**) Surveillance (years represent the start of surveillance in different areas), (**B**) Trapping approaches (CDC-trap and BG-trap with or without CO_2, and/or dipper), (**C**) Species composition, (**D**) Mosquito nuisance (colour bar indicates the nuisance scale), (**E**) Historical human West Nile virus cases in each country, (**F**) Mosquito operation approaches (Aircraft, track sprayers, and drone applications), (**G**) Mosquito control products (for immature stages: brown pile represents *Bacillus thuringiensis israelensis*, IGR = Insect growth regulator, and fish represents use of natural predators; for adults: use of synthetic chemicals are represented with a molecule symbol); targeted areas (rice fields, urban/suburban areas, and other habitats). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Nestos rivers, which have a high status of environmental protection. These river deltas are among the most important sites in Europe for supporting native and migratory birds, and several globally threatened avian species occur at these sites (Ramsar, 2024) (Table 1, Fig. 2).

Portugal: In the eighteenth century, incentives were introduced to cultivate rice primarily in the estuaries of Portugal's major rivers. Today, the main production areas are in the Vale do Tejo, Sado, and Mondego rivers. These regions, characterized by extensive wetlands and irrigated rice fields, create ideal breeding grounds for mosquitoes. With around 25,000 ha planted, Portugal accounts for about 6% of the rice field area in Europe, making it the fourth largest producer after Italy, Spain, and Greece (Table 1, Fig. 2).

France: France accounts for less than 5% of the total rice production in Europe. The primary region for rice cultivation is the Camargue (98% of rice production in metropolitan France), located in the southern part of the country. Other areas where rice is grown include the Aude Department (Occitanie Region) (less than 1% of France's rice production) and French Guiana (the only French overseas department to grow rice) (Table 1, Fig. 2).

3.2. Mosquito surveillance: species composition and abundance

Italy: Various monitoring programs have focused on mosquito vectors in rice paddies in northern Italy due to the high incidence of WNV in these areas since 2008. In Piedmont region, a law (75/95) was enacted in 1996 following an agreement among forty administrations to address mosquito proliferation and related complaints (Mosca et al., 2002). This regional law aimed to control mosquito populations and prevent VBD through a coordinated, long-term strategy. It emphasizes municipal collaboration, scientific expertise, and sustainable practices to safeguard public health and the environment. The law became fully operative a few years later, mainly around the rice-growing areas and major towns (Mosca, 2012). In Lombardy, a WNV surveillance plan has been applied since 2013, based on entomological monitoring and intensive surveillance of wild birds (Official Gazette, 2012). Starting from 2008 in Emilia-Romagna and in 2010 in the lowland areas of Veneto, a network of mosquito traps was set to monitor circulation of arboviruses (WNV and Usutu virus), within the national arbovirus surveillance and control plan, implemented at regional level. Most mosquito species exhibited a seasonal activity pattern, with abundance peaking in mid-summer (July–August). *Culex pipiens* and *Aedes caspius* are the most abundant species, with variable abundances over time (Figure S1 and Figure S2) (Fig. 3, Table 1 and references therein).

Spain: Mosquito monitoring in rice fields and adjacent wetlands in Spain is mainly conducted based on BG or CDC traps often baited with CO_2 (e.g. Figuerola et al., 2022; Roiz et al., 2014), along with landing rate observations and larval dipping, depending on the zones. Some regions in Spain, such as Valencia and Delta de l'Ebre, have historically monitored mosquitoes due to malaria outbreaks and mosquito nuisance (Bueno Marí, 2010). However, the recent increase in WNV circulation has prompted the execution of more focused local surveillance programs supported by research projects and new regional monitoring programs (e.g., Junta de Andalusia program). The most abundant species include *Culex theileri, Ae. caspius*, *Culex perexiguus,* and *Culex modestus*. *Culex. perexiguus* is present in south-west Spain rice fields and *Cx. modestus* in rice fields of east Spain (Bueno Marí, 2010; Cáceres and Ruiz, 2004; Roiz et al., 2015; Ferraguti et al., 2016) (Fig. 4, Table 1 and references therein).

Greece: To alleviate mosquito nuisance (Fig. S3), Greek authorities have implemented vector surveillance and management programs targeting rice-field environments with adjacent natural wetlands in the regions of Central Macedonia and Eastern Macedonia and Thrace. No systematic adult vector and arbovirus surveillance system was in place in the region of Thessaloniki prior to the major WNV outbreak in 2010. In Kavala, systematic mosquito surveillance was introduced in 2013 with standardized trapping methodologies, and in 2019, due to the high impact of WNV in the region, virus surveillance in mosquitoes and serological surveillance in sentinel chickens were incorporated into the existing network (Chaskopoulou et al., 2023). The most prevalent mosquito species identified in rice-field cultivation for both regions are *Ae. caspius*, *Cx. pipiens* and *Anopheles hyrcanus*. Other species were also detected in low numbers such as *Aedes vexans*, *Anopheles maculipennis* s. l., and *Cx. modestus*, among others. *Aedes caspius* populations have the highest activity during the beginning of the season, dropping significantly by July. In contrast, *Cx. pipiens* and *An. hyrcanus* populations peak in late summer (Fotakis et al., 2017) (Fig. 3, Table 1 and references therein).

Portugal: Portugal has implemented a comprehensive national vector surveillance program, focusing on areas around rice fields, under the National Vector Surveillance Program—REVIVE (REde de VIgilância de VEctores), operational since 2008 and oversee by the Portuguese Ministry of Health. This program monitors and provides key data for managing mosquito populations across the country, including surveillance of WNV and other arboviruses (CEVDI REVIVE, 2024). Intensive surveys conducted in the Sado estuary (Setúbal) and Ria Formosa (Algarve) in 2005–2006 showed high number of female mosquitoes per trap, with *Ae. caspius* being the most abundant species, constituting 95% of the total collection. Other species included *Anopheles algeriensis*, *An. maculipennis s.l., Coquillettidia richiardii, Cx. pipiens* s.l., *Cx. theileri, Culex univittatus, Culiseta annulata, Culiseta longiareolata, Ae. caspius,* and *Uranotaenia unguiculata* (Osório et al., 2008). Another survey from 2001 to 2004 found *Cx. theileri* to be the most abundant mosquito species in southern Portugal and in the rice fields of the Tagus and Sado river estuaries, particularly in the districts of Santarém and Setúbal (Almeida et al., 2008, 2010).

In the Comporta region, extensive mosquito surveillance has been part of broader efforts to manage populations and monitor mosquito-borne diseases like WNV. From 2004 to 2007, systematic surveillance using CDC light traps and indoor resting collections identified a diverse mosquito population predominantly composed of *Cx. theileri* (85% of captures), followed by *Ae. caspius, Anopheles atroparvus*, and *Cx. pipiens*. Surveillance in both wetland areas of Comporta and around Alqueva's artificial lake (Alentejo region, not associated with rice field activity), indicated significantly higher mosquito densities in Comporta, underscoring its status as a hotspot for mosquito activity. The REVIVE program, operational since 2008, further emphasizes the importance of ongoing monitoring in the region, focusing on detecting invasive species and providing essential data to health authorities to mitigate public health risks (Fig. 3, Table 1 and references therein).

France: Active surveillance is implemented by the EID-Méditerranée (the public mosquito operator for the French Mediterranean coast) since 2008. However, *Culex* spp. and *Anopheles* spp. ethology in the Camargue area has been studied since 2002. Two pestiferous mosquito species (*Ae. caspius* and *Aedes detritus*), are particularly monitored along the French Mediterranean coast, especially, in the Camargue area, but not in rice fields itself. The main mosquito species associated with rice fields are *Cx.*

Table 1
Summary of rice field cultivation, mosquito surveillance, and major nuisance and vector species in the five major rice-growing countries of Europe (Italy, Spain, Greece, Portugal, and France).

Country	Region (coordinates)	Rice field areas (ha)	Extension	Surveillance	Traps	Mosquito species	Nuisance and VBD	References
ITALY	Piedmont 45.05° N, 7.92° E	ca. 113,500	Vercelli (71,136 ha), Novara (30,974 ha), Alessandria (7,450 ha) and Biella (3,894 ha)	Active entomological surveillance since 1998 Wildlife and human surveillance since 2012	CDC traps baited with dry ice. Weekly (May/June to September/October)	Aprox. 20 mosquito species recorded. Mainly *Ae. caspius* and *Cx. pipiens.* Other species in lower proportions: *An. maculipennis* s.l., *Ae. vexans* and *Cx. modestus*	Significant impact on humans and animals due to high *Ae. caspius* populations. Malaria outbreaks in the past. 10% of the total WNV human cases occur in this region	Bisanzio et al. (2011); Mosca et al. (2010); Mosca (2012); Mosca et al. (2002); Piazzi and Mosca (2009)
	Lombardy 45.65° N, 9.96° E	ca. 92,800	Pavia (mainly), Milán and Mantua (minor extent)	Entomovirological and wildlife surveillance program since 2013	CDC traps baited with dry ice Weekly (June to October)	Aprox. 9 mosquito species. The most abundant are *Cx. pipiens* and *Ae. caspius* (both accounted for 87.5% in similar proportions) followed by *An. maculipennis* s.l. (11.4%)	Malaria historically, current circulation area of WNV (high transmission risk) and Usutu virus	Official Gazette (2012)
	Emilia-Romagna 41.89° N, 12.40° E	ca. 6,300	Near the Po river delta and in the central part of the region (between provinces of Reggio Emilia and Modena)	Entomological network under the frame of the arbovirus surveillance since 2008. Wildlife surveillance since 2009	CDC traps baited with dry ice Biweekly (May to October)	*Culex pipiens* (49%) and *Ae. caspius* (46.5%) in similar proportions (2021–2023). Other 9 species such as *Ae. vexans* and *An. maculipennis* s.l., in lower proportion	*Ae. caspius* nuisance, malaria historically and circulation area of WNV and other arboviruses including Usutu, but not associated with rice field areas	Calzolari et al., (2023, 2022)
	Veneto 45.26° N, 12.19° E	ca. 3,000	Verona province (3/6), followed by village of Isola Della Scala (2/6), and in the Rovigo province (1/6)	Entomovirological monitoring in the frame of the WNV (surveillance since 2009)	CDC-like traps baited with dry ice. (May to October). Additional sampling with other methos were also conducted	17 mosquito species including adjacent areas. *Cx. pipiens* (77.5%) and *Ae. caspius* (11.4%)	*Cx. pipiens* nuisance. Malaria endemic historically. WNV and Usutu circulation region but not associate to rice fields	Angeloni et al. (2023); Bertola et al. (2022); Fornasiero et al. (2020); Mencattelli et al. (2022)
SPAIN	Marismas del Bajo Guadalquivir 37.09° N, 6.14° W	ca. 35,000–40,000 [a]	Nine main municipalities. The most important economic activity in Isla Mayor (Sevilla)	2000–2020 sporadically surveillance. Active entomovirological surveillance since 2020 (as consequence of WNV in humans)	Mainly BG-sentinel traps baited with dry ice	Aprox. 6 mosquito species. *Cx. theileri* (mainly) and *Cx. perexiguus*	Current WNV circulation area. The high-risk hotspot in Spain is clearly associated with rice fields	Ferraguti et al. (2016); Figuerola et al. (2022); Roiz et al. (2014)
	Vegas Altas 38.12° N, 5.56° W	ca. 21,000	22 municipalities (Badajoz)	Sporadic entomological surveillance (2018–2020) in rice fields	BG-sentinel and CDC light traps baited with dry ice	Aprox. 10 mosquito species. *Ae. caspius* and *Cx. pipiens* in similar proportions	Malaria endemic area and WNV circulation hotspot in surrounding municipalities	Bravo-Barriga et al. (2021); Diputación de Badajoz (2021)
	Delta de l'Ebre 40.43° N, 0.44° E	ca. 20,000	Distributed throughout 7 municipalities in the Delta de l'Ebre (Tarragona)	Active entomological surveillance in specific sampling points	Larvae (dipping) and aspirations on humans	*Culex modestus* and *An. atroparvus. Ae. caspius* in wetlands	Moderate nuisance, malaria foci in the past and human sera detected against WNV and other flavivirus in the 1980s	Lozano and Filipe (1998)
	Albufera 39.17° N, 0.20° W	ca. 15,300 of rice surrounded by 3,000 ha of a freshwater lagoon	Around 14 municipalities located in the Natural Park of Albufera (Valencia)	No routine surveillance. Since 2022, entomological surveillance mostly based on the collection of aquatic forms	Larvae (dipping) Weekly (active search of larvae by dipping)	Aprox. 10 species. The most abundant *Cx. modestus* and *Cx. pipiens*	Nuisance by *Aedes* species and very important malaria foci in the past. Not VBD associated to rice fields so far	Bueno Marí et al. (2010); Rueda et al. (2017)
	La Janda	ca. 3,000 (2,700 ha in 2018)	4 municipalities in the Janda	Entomological surveillance.	Larvae (dipping) and	*Cx. theileri, An. atroparvus,* and	High nuisance by *Ae. caspius* in	Cáceres and Ruiz (2004)

(continued on next page)

Table 1 (*continued*)

Country	Region (coordinates)	Rice field areas (ha)	Extension	Surveillance	Traps	Mosquito species	Nuisance and VBD	References
	36.27° N, 5.55° W		region: Vejer, Barbate, Tarifa, and Benalup-Casas Viejas (Cádiz)	From 2002 to 2013 (weekly)	CDC light traps without dry ice	*Ae. caspius* (tidal marsh of Barbate)	tourist areas; WNV outbreaks since 2010	
Country	Region (coordinates)	Rice field areas (ha)	Extension	Surveillance	Traps	Mosquito species	Nuisance and VBD	References
GREECE	Thessaloniki Regional Unit 40.63° N, 22.73° E	ca. 20,000 (slight variations from year to year)	Delta and Chalkidona municipalities (Axios River plains)	Since 2011, vector and pathogen systematic surveillance system (avian and horse indicators) (weekly/biweekly from May to November)	Primarily CDC light traps baited with dry ice and various forms of sentinel animal networks	*Ae. caspius, Cx. pipiens* s.l. *(pipiens form* is the dominant, followed by *hybrids* and *molestus),* and *An. hyrcanus*	High nuisance WNV outbreaks since 2010	Chaskopoulou et al., (2010); Chaskopoulou et al. (2013); Fotakis et al. (2017); Miaoulis et al. (2018); Piakis et al. (2007)
	Kavala Regional Unit 40.98° N, 24.70 °E	ca. 1,300 (slight variations from year to year)	Nestos municipality (Nestos River plains)	Vector and pathogen surveillance (weekly/biweekly)	Primarily CDC light traps baited with dry ice and various forms of sentinel animal networks	*Ae. caspius, Cx. pipiens, An. hyrcanus*	High nuisance WNV outbreaks since 2012	
PORTUGAL	Mondego river 40.12° N, 8.79° W	ca. 7,000	Municipalities of Figueira da Foz, Coimbra, and Montemor-o-Velho	Sporadically before 2008 Since 2008, National Entomological Network (REVIVE)	CDC traps baited with dry ice. Weekly (June to October)	*Ae. caspius, Cx. pipiens* and *Cx. theileri*	No nuisance information/study No VBD in the area	Almeida et al. (2008, 2010); CEVDI REVIVE (2024); Osório et al. (2008); Saavedra (2010); Zé-Zé et al. (2015)
	Tagus Estuary 38.75° N, 8.95° W	ca. 14,300	Benavente, Vila Franca de Xira and Alcochete	Vector and pathogen surveillance (weekly/bi-weekly)		*An. maculipennis* s.l., *Ae. caspius, Cx. pipiens* and *Cx. theileri*		
	Sado tributaries 38.56° N, 8.73° W	ca. 9,000	Setúbal, Alcácer do Sal, Grândola and Palmela			*Ae. caspius, An. maculipennis* s.l., *Cx. pipiens, Cx. theileri* and *Cx. univitattus*	Nuisance by *Ae. caspius* and *Cx. theileri*. Former malaria hyperendemic region in the 20th. WNV circulation in birds and horses. WNV human in 2015	
FRANCE	La Camargue 43.32° N, 4.31° E	ca. 12,400 (a reduction is observed along time)	Between Bouches-du-Rhône (to the east) and the Gard (to the west)	Since 2008, active surveillance is implemented by the EID-Méditerranée	CDC-like traps baited with CO_2. Weekly (April to October. From 2002 to2006	*Cx. modestus, Cx. pipiens, An. hyrcanus* and *An. maculipennis* s.l.	Nuisance by *Ae. caspius*, endemic for malaria and WNV circulation area since 2015	Bahuon et al. (2016); Constant et al. (2022); Ponçon et al. (2007)

[a] High variation depending on water availability, i.e. in 2022 only 2000 ha were cultivated and in the year 2023 around 13,000 ha.

modestus, Cx. pipiens, An. hyrcanus and *An. maculipennis* s.l. The activity of both *Cx. pipiens* and *Cx. modestus* peak in mid-July, while *Ae. caspius* activity peaks between April and May. *Culex* spp. and *Anopheles* spp. primarily develop in the rice fields from May to August (Fig. 3, Table 1 and references therein).

3.3. Mosquito nuisance and VBD background

Italy: In the extensive rice farming region of the Po valley, mosquito nuisance is linked mostly to the presence of *Ae. caspius*. The high level of nuisance has led the initiation of intensive mosquito control measures (Talbalaghi et al., 2002). Italy reported the highest number of human WNV cases (n = 588 confirmed cases) in Europe in 2022, with the majority of cases concentrated in the Po river valley (ECDC, 2023a). Since 2008, WNV outbreaks have occurred annually in this area, spreading from their initial northern foci throughout the country. During the largest WNV outbreak in 2022, most human cases were reported in Veneto (57.5%), followed by Emilia Romagna (15.5%), Lombardy (11.8%), Piemonte (9.7%), and Friuli-Venezia-Giulia (3.1%) (IZS, 2022). Although Usutu virus is also widespread in these areas, only few human infections have been reported (Angeloni et al., 2023). Tahyna virus was detected in *Ae. caspius* mosquitoes from Emilia-Romagna (Calzolari et al., 2022, 2023) (Table 1).

Spain: Mosquito nuisance is reported in urban areas close to flooded areas rice fields, mainly due to the presence of *Ae. caspius*, *Ae. detritus,* and *Cx. modestus*. Since 2004, WNV has been a major concern in the country. The largest transmission event occurred in the summer of 2020, when a significant and unexpected outbreak resulted in 77 cases and 8 deaths, affecting many municipalities near rice cultivation areas (García San Miguel et al., 2021). WNV-positive mosquitoes were detected in two villages (Puebla del Rio and Coria del Rio) around the Marisma del Bajo del Guadalquivir, with positive seroprevalence recorded in urban birds (Figuerola et al., 2022). Recent human WNV cases in new areas of Extremadura and Valencia, often near rice paddies, have raised additional concerns (ECDC, 2023a; Macias et al., 2023) (Table 1).

Greece: The previous described regions in Greece host some of the

Table 2
Summary of mosquito control approaches in the five major rice-growing countries of Europe (Italy, Spain, Greece, Portugal, and France).

Country (region)	Adulticides	Larvicides	Biological, enviromental and physical solutions	Organism that executes control actions	Organism that funds control actions	Other remarks
ITALY Piedmont	Only in urban and suburban areas after exceeding certain nuisance thresholds, in conjunction with public events, or after human cases of VBD	Application of larvicide in rice fields: *Bti* (2000–2014) by space spraying with aircrafts Diflubenzuron (2007–2015) by ground with tractors	Mosquito fish (*Gambusia holbrooki*) was experimentally tested Extend the periods of submergence of the paddies Provide the rice fields with ditches to retain some water after drainage	Municipality-based (2000–2006), regional-based (2007–2015)	Regional government funds (NUTS2), with additional funding from provinces (NUTS3) or municipalities	Field inspectors check rice paddies twice a week. European Rural Development Programmes (RDPs) have financed additional interventions
Lombardy	Only in urban and suburban areas (after WNV human episodes)	Application of larvicide *bti* during pre-sowing in water, during sowing in rice water, and on the banks of the uncovered irrigation ditches in the agricultural water distribution system	Sowing underground on dry soil and temporary flooding of the rice fields	Private sector (Pest Control Specialized Private Companies)	Regional government funds (NUTS2), with additional funding from provinces (NUTS3) or municipalities	NA
Emilia-Romagna	Only in touristic areas after exceeding certain nuisance thresholds or in particular situations for VBD circulation	Larvicide applications in touristic areas	No	Municipality-based (2000–2006) and regional-based (2007–2015)	Regional government funds (NUTS2), with additional funding from municipalities	NA
Veneto	No	No specific actions	No	Private sector (Pest Control Specialized Private Companies)	Regional government funds (NUTS2), with addtional funding from provinces (NUTS3) or municipalities	NA
SPAIN Marismas del Bajo Guadalquivir	Only in urban and suburban areas (after WNV episodes)	Not as a routine. Larvicide treatments with *bti* after WNV human cases outbreaks	A large tower (12 m and 300 nests) was installed in the most important urban area affected with human WNV to support bats and insectivorous birds	Private sector (Pest Control Specialized Private Companies)	NA	NA
Vegas Altas	Micro-capsulated cypermethrin or permethrin in urban areas	Since 2022. Application of *bti* treatments in "belts or buffer zones" surrounding rice fields (three treatment per year)	Installation of nest boxes in several places. Pilot studies with native fish such as Fartet (*Aphanius Iberus*) and Samaruc (*Valencia hispanica*) yielded variable results	Private sector (Pest Control Specialized Private Companies)	Diputación de Badajoz (Public Entity)	Continuity of operation is not guaranteed
Delta de l'Ebre	No	Since 1991. Aerial spraying (two units) of *bti* using hydraulic nozzles for dispersal in 500 m wide "belts or buffer zones" (4 treatments per year)	No	COPATE-Consortium specialized team operators	Generalitat de Catalunya (50%), Diputació de Tarragona (25%) and the local councils (25%)	Well-established operation mode actions
Albufera	Very rarely (pyrethroids) in urban areas (high populations of mosquitoes or chironomids)	Application of larvicide *bti*, using handheld equipment spraying in specific breeding sites in adjacent waterlogged environments (marshes and ditches) but not inside rice fields	Mosquito fish (*Gambusia holbrooki*) was experimentally tested. Extend the periods of submergence of the paddies or provide the rice fields with ditches to retain water after drainages	Private sector (Pest Control Specialized Private Companies)	Consorci de la Ribera, municipalities and others	NA
La Janda	Pyrethroids on peri-urban zones	Between 2006 and 2015, aerial treatment with *bti* on rice fields and peri-urban zones	No	From 2006 to 2013, managed by rice farmers through public control pest control service; From 2013-18, by a private company	Diputación Provincial de Cádiz (Public Entity)	NA
GREECE Thessaloniki Regional Unit Kavala Regional Unit	Aerial space ULV spray pyrethroid applications targeting agricultural environments; ground ULV space spray pyrethroid applications	Aerial (high volume) applications of a *bti*-based products targeting rice fields and natural environments. Ground (high-volume)	NA	Regional government authorities are responsible for administering, supervising and funding of vector control	All vector control programs in Greece follow national guidelines for the design and implementation of vector control strategies,	NA

(continued on next page)

Table 2 (*continued*)

Country (region)	Adulticides	Larvicides	Biological, enviromental and physical solutions	Organism that executes control actions	Organism that funds control actions	Other remarks
	targeting urban environments; residual surface spray pyrethroid applications in urban environments. Adulticides are applied in response to increased risk of WNV transmission as determined by vector surveillance indicators and human cases	applications of *bti* or/and Insect Growth Regulator-based products targeting breeding sites in peri-urban/urban environments		operations. Private agencies are subcontracted to implement vector control treatments under the umbrella of Integrated Vector Management	abiding by the principles of Integrated Vector Management	
PORTUGAL Mondego river Tagys Estuary Sado Tributaries	Pyrethroids are used to combat other rice pest species, often in conjunction with other phytosanitary herbicides and fungicides. Treatment against adult mosquitoes may be carried out in urban areas in exceptional situations	NA	NA	None	None	NA
FRANCE La Camargue	Treatment against adult mosquitoes may be carried out in urban areas in exceptional situations	Application of larvicide *bti* since 2005, but not specifically in rice fields but in flooded areas	NA	EID-Méditerranée (the public mosquito operator for the French Mediterranean coast)	State (Government)	Well-established operation mode actions

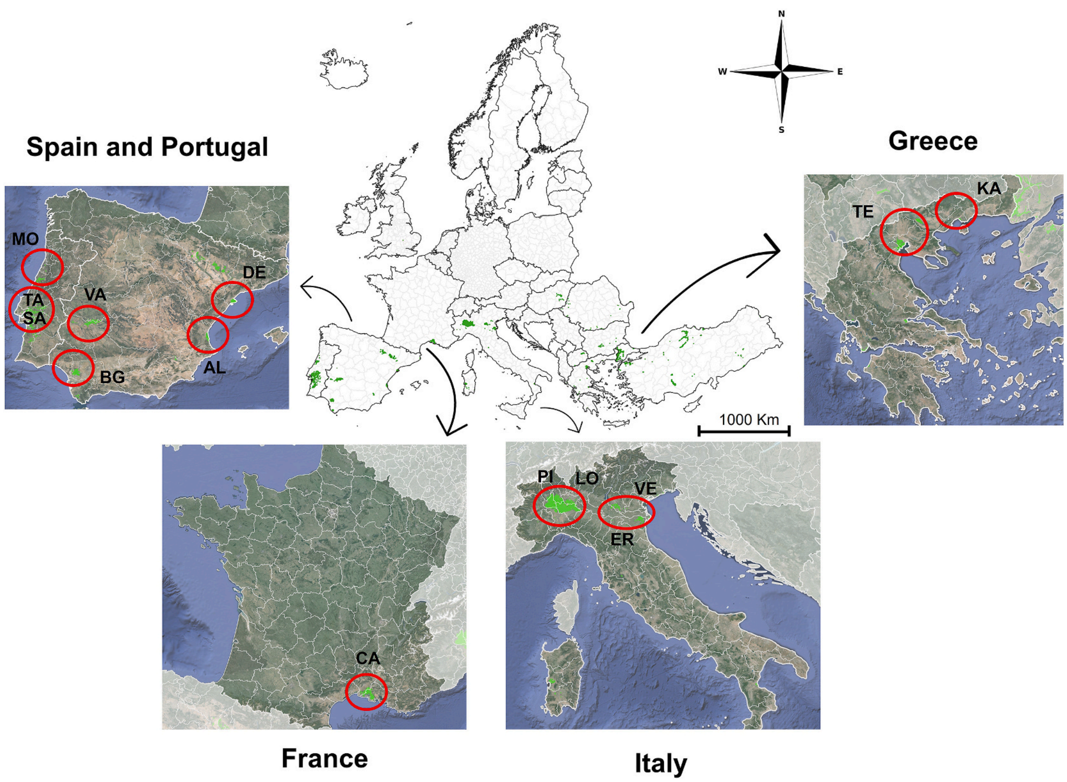

Fig. 2. Five main rice field cultivation countries in Europe over the 21st century. Red circles denote the main rice field local areas. Italy (PI: Piedmont, LO: Lombardy, ER: Emilia-Romagna, VE: Veneto), Spain (BG: Marismas del Bajo Guadalquivir, VA: Vegas Altas, DE: Delta de l'Ebre, AL: Albufera), Greece (TE: Thessaloniki Regional Unit, KA: Kavala Regional Unit), Portugal (MO: Mondego river, TA: Tagus Estuary, SA: Sado tributaries), France (CA: La Camargue). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

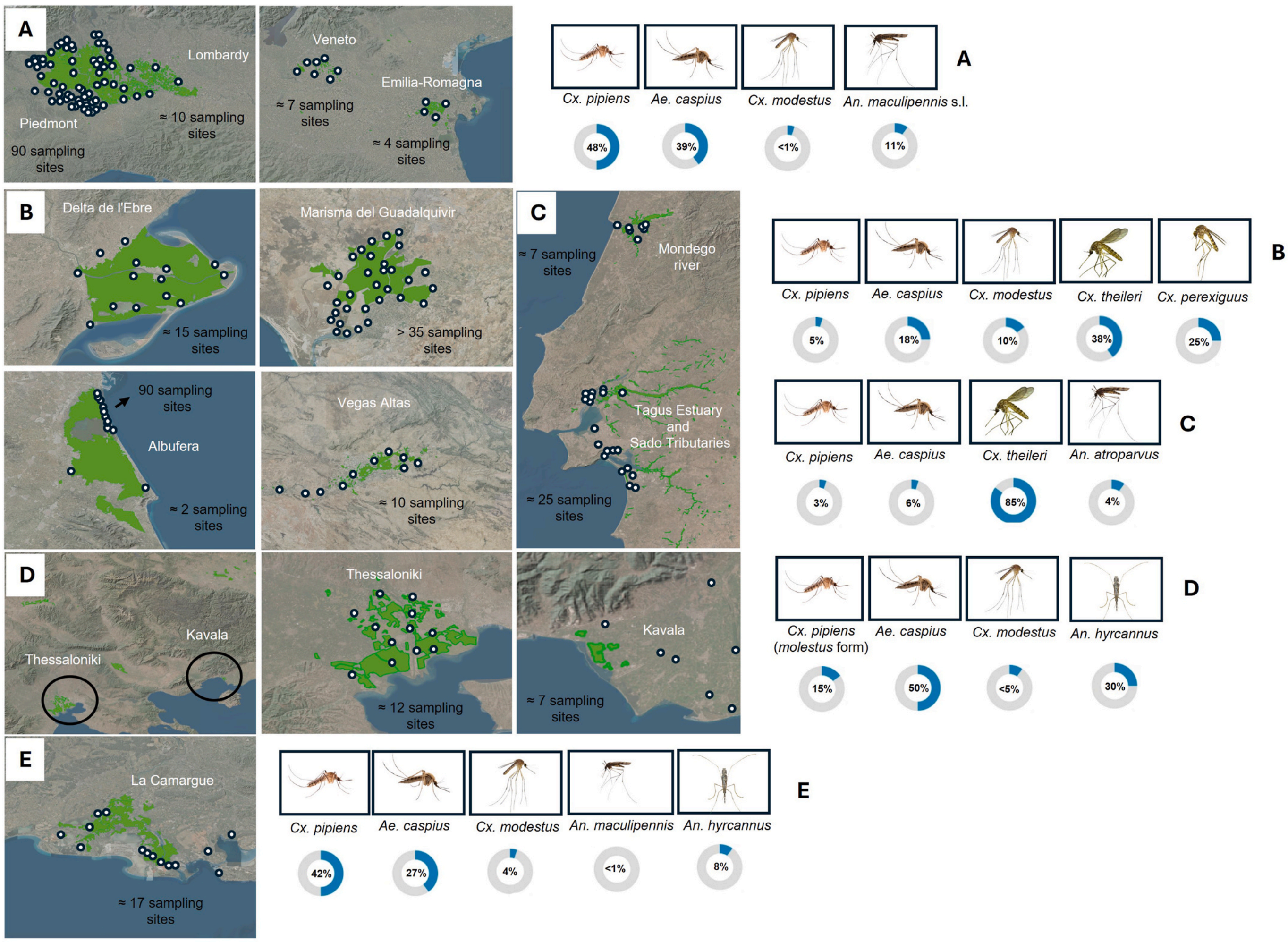

Fig. 3. Location of the sampling sites and relative species composition of mosquitoes in the 14 major rice-growing areas in Europe. (**A**) Italy (Piedmont, Lombardy, Emilia-Romagna, Veneto), (**B**) Spain (Delta de l'Ebre, Marismas del Bajo Guadalquivir, Albufera, Vegas Altas), (**C**) Portugal (Mondego river, Tagus stuary, and Sado tributaries), (**D**) Greece (Thessaloniki Regional Unit and Kavala Regional Unit), (**E**) France (La Camargue). Species composition is calculated based on the average abundance of mosquitoes collected using different trapping systems throughout the monitoring periods (Table 1 and references therein). Please note that species composition varies by the season and year. Only sampling sites located in rice fields and adjacent areas are represented. The location of some sites is approximate due to the alack of specific coordinates.

largest (in terms of areas treated), most comprehensive, centrally administrated vector control programs in the country. The extensive flooded environments (both natural wetlands and rice fields) result in high mosquito production rates, causing significant nuisance in surrounding residential and urban areas (Chaskopoulou et al., 2010). Traps deployed in and near these regions regularly collect over 10.000 adult mosquitoes per trap per night during the summer months (Chaskopoulou et al., 2023). The agricultural region of Thessaloniki was in the epicenter of one of the largest WNV outbreaks reported in Europe in 2010, with 262 clinical cases and 35 fatalities (Chaskopoulou et al., 2011b). Human cases have been reported in the region every year from 2010 to 2014 and from 2018 to 2023. In Kavala, human cases of WNV have been systematically recorded, with outbreaks in 2012, 2013, 2019, 2020, and 2023. Based on evidence from the WNV regional surveillance network involving mosquitoes and sentinel chickens, the highest WNV infection and seroconversion rates have been consistently reported from the rice-field region of the Nestos River plains, indicating that this habitat plays an important role for the amplification of WNV in nature (Table 1).

Portugal: Currently, there are no documented records of perceived mosquito nuisance or studies addressing mosquito-related disturbances in Portugal. In areas with flooded rice fields, WNV poses a significant public health concern (Geraldes et al., 2024). Initial evidence of WNV activity in Portugal was noted in the late 1960s through serological surveys conducted in the southern regions during 1966–1967 (Filipe and Pinto, 1969). Confirmed cases of autochthonous WNV infections in humans were not reported until 2004 and mosquitoes of the species *Cx. pipiens* and *Cx. perexiguus*, carrying WNV, were identified near the suspected area of infection (Connell et al., 2004; Esteves et al., 2006). Additional cases were reported in 2010 and 2015 (Alves et al., 2012; Zé-Zé et al., 2015). Overall, the evidence indicates that WNV circulation in Portugal is primarily confined to the southern parts of the country, particularly in the districts of Faro and Setúbal, where rice field cultivation is practiced alongside other crops (Table 1).

France: The nuisance caused by *Ae. caspius* is primarily limited to the salt marshes and the initial flooding of rice fields rice fields. Rice fields are typically located far from urban areas, which reduces the nuisance associated with *Culex* spp. Malaria was a major health problem in the Camargue until eradication, while WNV is now an endemic VBD (Constant et al., 2022). The first WNV epizootic was reported in the Camargue region in 1962, and the involvement of *Cx. modestus* in WNV transmission has been established in the Camargue since 1970 (Filipe and Pinto, 1969; Filipe, 1972). Since then, several WNV outbreaks have occurred, notably in 2000, 2003, 2004, 2006, 2015, and 2017. A

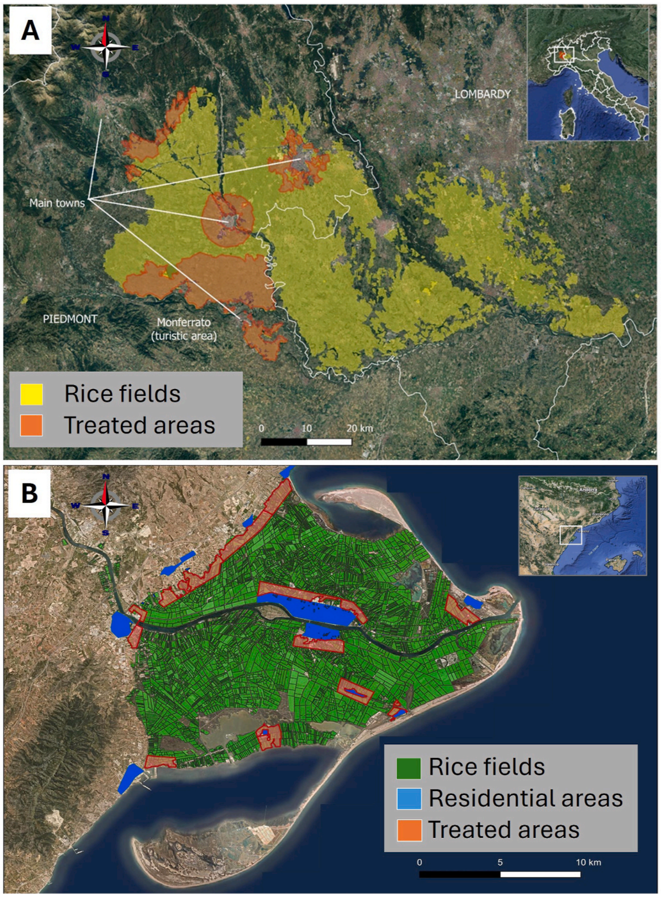

Fig. 4. Examples of the two rice field areas in Europe with well-structured control approaches. Piedmont (northern Italy) (**A**) and Delta de l'Ebre (northern Spain) (**B**). In both regions, mosquito control approaches are mainly focused around residential areas to protect human populations from mosquito bites and VBD.

surveillance system monitoring humans, horses, and birds indicates regular circulation of WNV (EID data-unpublished), underscoring the fact that the Camargue area provide favorable conditions for WNV amplification (Bahuon et al., 2016) (Table 1).

3.4. Mosquito control approaches

Italy: Piedmont is the region that has implemented more effort and strategies to reduce mosquito abundance. Initially, highly polluted rice field breeding sites were treated with temephos, an organophosphate authorized in EU until 2006. Later on, diflubenzuron, a benzamide inhibiting the production of chitin, was employed, while *Bacillus thuringiensis* var. *israelensis* (*bti*) is used in non-polluted areas (Bisanzio et al., 2011). As the rice cultivation area is too vast to be treated entirely with larvicides, from 2000 and for more than a decade, rice paddies were treated in belts (buffer-zones) of about 10 km around the main inhabited centers and tourist areas (Fig. 4a). The primary treatment method was aerial spraying of *bti* water suspensions (Piazzi and Mosca, 2009). Since 2007, to reduce the economic cost of aerial applications and to increase effectiveness, rice growers used rice seeds treated with diflubenzuron (Mosca and Roberto, 2007). Despite achieving a reasonable reduction in the larval populations (up to 80%) in the field, adult populations monitored with a network of CO_2-CDC traps only experienced an average reduction of 50%. After more than a decade of larval control applications, all interventions (both *bti* and diflubenzuron) were suspended in 2016. As a result, *Ae. caspius* populations began to increase from 2019 onwards, eventually returning pre-intervention levels (Figs. S1 and S2).

In the other regions of Italy, actions are not as well-established as in Piedmont, and no specific interventions are performed in rice fields except in touristic places, urban areas, and/or during extraordinary mosquito infestation and/or local outbreaks. The control of mosquito species that occur in rice fields (mainly *Ae. caspius*) is carried out with the collaboration of rice farmers and the support of the municipality. Costs and their distribution among the financing bodies have varied over the years. The annual cost ranged from 5 to 8 million Euros, supported by the participating provinces and municipalities (with up to 20% of the total funds) and the Piedmont Region (with 80–100% of the total funds) until the end of the operations in 2015 (Table 2).

Spain: Different actions and operation strategies are employed in flooded rice-field areas. For example, in Delta de l'Ebre (Catalonia), mosquito control has been carried out since 1991 by a public consortium (currently named COPATE). Approximately 10% of the rice fields are included in the control program. Due to the economic and logistical challenges of controlling mosquito larvae in such a large region, selective strips (ca. 500 m wide perimeter barriers) surrounding 11 villages and residential areas are treated with *bti* larvicide (Fig. 4b). This strategy has led to a notable reduction in the density of mosquito larvae in the areas close to human populations. Although these measures seem adequate for controlling *An. atroparvus*, they have not been successful in managing *Cx. modestus,* which is now the predominant species in this area. In the Albufera (Valencia), mosquito control has been a common practice in protected natural wetlands and, nowadays, is performed by specialized pest control companies. The main problem is concentrated on marshes (known as malladas in Spanish), the surrounding main lagoons, and ditches whereas whereas rice paddies are usually located further insidedSince 2022, a specific action plan has been established by affected municipalities to combat mosquito populations in rice fields in Vegas Altas (Badajoz) (Diputación de Badajoz, 2021), executed by private pest control companies. Interestingly, rice fields in Bajo Guadalquivir do not receive specific mosquito control measures. Despite this area is the hotspot of WNV human cases in Spain since 2020, no comprehensive vector control plan has been adopted for the rice fields, even though *Cx. perexiguus* – the main vector of WNV in the area – is associated with rice production (Ferraguti et al., 2016; Figuerola et al., 2022). This is partly due to the main rice farmer's association questioning the role of rice fields in mosquito breeding. Following the significant WNV outbreak in 2020 in Bajo Guadalquivir, adulticide and larvicide treatments were initiated in the affected villages, carried out by different private companies contracted by local municipalities (García San Miguel et al., 2021). Larvicide treatments with *bti* were conducted in urban scuppers and larval habitats within 2 km of urban areas. Adulticide treatments, using pyrethroids primarily through ULV spraying and residual spraying, were also conducted in the residential areas near rice paddies (Figuerola et al., 2022). In subsequent years, similar responses were made at a smaller scale when WNV-positive mosquito pools were detected, focusing mainly on urban areas but occasionally extending to rice fields when WNV circulation intensities reached very high levels (as in 2024).

Funding for the control of mosquitoes in rice fields varies significantly. For example, in Catalonia, the control program is funded by contributions from various administrations, whereas in Valencia, it is assigned to pest control companies through the Consorcio de la Ribera (Diputación de Valencia, a public entity). Similarly, in Badajoz the program is supported by the Diputación de Badajoz, a public entity. In some regions, agricultural farmers receive economic support from the European Union in exchange of using environmentally friendly methods, such as winter flooding or using a reduced number of phytosanitary products, applied only when certain damage thresholds are detected. In the last years, the winter flooding requirement has stopped due to severe drought and WNV outbreaks in the area. Unfortunately, using environmentally friendly products and methods for mosquito control is not included as a requisite to obtain these funds.

Consequently, municipalities affected by mosquitoes born at the nearby rice fields must use their own budgets to pay for mosquito control (Table 2).

Greece: Local vector control programs funded by the Greek government (regional and/or national funds) have been implemented in Thessaloniki since 1997 (ECDC, 2020) and since 2000 in Kavala (Piakis et al., 2007). Regional departments of public health supervise vector control operations in both regions, while private entities execute the operations. Before the detection of WNV in the country, the only mosquito control method was larviciding and the vast majority of vector control efforts were focused on nuisance management (ECDC, 2020). As a result of the WNV threat, exemption permits from the Ministries of Agriculture and Health were issued in 2010 for ground and aerial ultra-low volume (ULV) space spray applications with pyrethroid insecticides against adult mosquitoes. The aerial ULV treatments were optimized locally for efficacy, precision, and reduction of non-target effects in a three-year longitudinal study (2008–2010) in the region prior to issuance of permits (Chaskopoulou et al., 2011a; Chaskopoulou et al., 2014). Exemption registrations continue to be issued for both regions in Greece as requested by regional public health authorities. Today, the main vector control operations in both regions consist of aerial larviciding with biological products (*bti*) targeting rice fields and natural wetlands, ground larviciding (*bti*/insect growth regulators) targeting irrigating canals and other semi-urban/urban breeding sites, and ground residual adulticiding with pyrethroid-based products targeting resting adult mosquitoes (Chaskopoulou et al., 2016). Aerial or ground ULV space spray applications are conducted in response to elevated WNV transmission risk, targeting agricultural/rice-field regions and peri-urban/urban areas, respectively (Table 2).

Portugal: No control actions targeting mosquitoes are performed in the rice cultivation areas. However, pyrethroids used to combat other rice pests can be applied in conjunction with other phytosanitary products like herbicides and fungicides (Agriterra, 2021). The Comporta region has also been a testing site for *bti*, demonstrating its effectiveness in reducing local mosquito populations under field conditions, offering an environmentally friendly option for mosquito management (Novo, 2008) (Table 2).

France: More than 90% of French rice cultivation is located in protected areas (Camargue Regional Nature Park and/or UNESCO Biosphere Reserve), requiring rice growers to adopt environmentally friendly farming practices (Table 2). EID-Méditerranée started using *bti* biolarvicide treatments here following a major mosquito outbreak in 2005, which prevented schoolchildren in the Camargue and surrounding cities from using school playground. This program aims to reduce the nuisance to an acceptable level while maintaining the natural balance, and its activities are not typically linked to rice production. If treatment is required, *bti* is the only product approved for use in a natural environment. In the case of VBDs, reactive surveillance is the approach, meaning an entomological study is conducted only when a case of WNV is detected. To date, no adulticide have been used in the Camargue region (neither in natural or urban foci) for mosquito control related to WNV cases.

3.5. Operational challenges in managing mosquito populations in intensive rice-agroecosystems

i) Regulatory constraints, product availability, and high costs: The limited number of registered biocidal products is reported as the most important barrier to effective vector control strategies in rice-field environments (ECDC, 2020). Over the past two decades, the number of registered products for vector control in Europe has gradually decreased, primarily for economic reasons. The vector control product market is extremely small - merely 2% of the global chemical crop and non-crop market (Lucas, 2014) – making it difficult to support the efficacy and safety studies required for product registration in the European Union. This may explain why there is a wide range of insecticidal products registered for agricultural pest management, while there are very few products specifically tailored for mosquito control. In addition, regulatory restrictions prevent or limit aerial applications for vector control, leading to the interruption of interventions in rice fields (e.g., Italy). The limitations or lack of availability of products with high residual activity directly impact both the frequency of the treatment and the size of the treated areas (e.g., Italy and Greece). In Europe, only one biological larvicide (i.e. *bti*) alone or mixed with *Bacillus sphaericus* is available for treating rice fields and natural wetlands. However, it is costly and has limited residual efficacy, affecting the sustainability of larviciding operations in large agroecosystems.

ii) Insufficient larviciding treatment zones: Due to economic constrains, larviciding treatments are often applied in buffer zones (belt-barriers) rather than over large areas of productive rice fields. In many cases, this partial coverage is insufficient to protect inhabited areas from mosquitoes due to rapid dispersal from adjacent untreated areas (e.g., Italy). The size of treatment zones needs to be reassessed, considering the flight capacities of each targeted mosquito species.

iii) Lack of a timely larval surveillance system: It is not feasible to survey every rice field for the presence of larvae, leading to gaps in treatments. Surveillance zones that serve for the monitoring of the entire region should be identified and used as an early indicator to trigger larvicidal applications. Developing local expertise on larval productivity in the field is crucial for determining the appropriate timing and spatial placement of treatments (e.g., Italy).

iv) Rice farmers objection to vector control interventions: In the largest rice field cultivation region and major WNV hotspot in Spain (Bajo Guadalquivir), the rice farming community opposes the use of control measures due to conflict of interests regarding biocides use and the economic costs of the operation. In other areas of Spain, there is a lack of transparency regarding local pesticide use, as rice fields are privately owned. The survey done suggests that the economic costs derived from mosquito control operations do not rely on the farmers but are covered by different public administrations. A collaborative framework under the One Health approach is needed to address nuisances arising from agricultural ecosystems, involving all relevant stakeholders: local and regional authorities, farmers, animal and public health professionals, vector control operators, and natural wetlands management authorities.

v) Pesticide resistance: There are concerns about the development of pesticide resistance to pyrethroids (the only group of active ingredients available for adulticiding), emphasizing the need for a broader range of products and active ingredients to address this issue (Kioulos et al., 2014; Vereecken et al., 2022; Pichler et al., 2022; ECDC, 2023b).

vi) Limited experience and scientific evidence: There is insufficient knowledge and scientific data on the use, effectiveness, and scalability of restoring local populations of bats and insectivorous birds for controlling mosquito populations at the landscape level (Puig-Montserrat et al., 2020). The autochthonous fish species that may contribute to larval control are highly endangered, rendering their impact on mosquito larvae populations negligible. An alternative could be the use of the invasive fish species *Gambusia* spp. (Valter et al., 2017), which is already present in these areas, but its reproduction and transport are restricted in Europe [EU Invasive Alien Species Regulation (1143/2014)], limiting practical application. In addition, a better knowledge of the impacts of this species on other invertebrates, such as dragon flies in rice fields, would be necessary. While natural predators are unlikely to control rice field associated mosquito populations by themselves, they may help to reduce their impact on urban areas. Population awareness campaigns to preserve swallows, other insectivorous bird nests, and bats refugees in the rice production and the nearby urban areas, along with scientific studies to quantify their impact on mosquito populations, are urgently needed to diversify the toolkit available for mosquito control. Barrier traps, used for massive mosquito capture, effectively reduce overall mosquito abundance (Poulin et al., 2017; Pontifes et al., 2024). However, it remains unclear whether these methods are effective to protect large urban areas.

4. Discussion and moving forward

Through this study, we have summarized the information available on mosquito communities, VBD risk, and mosquito management strategies for all the major rice agroecosystems in Europe. Many of these regions were historically known to be endemic foci for malaria transmission in past centuries and have recently been associated with WNV enzootic and epizootic outbreaks. Overall, mosquito surveillance programs have been implemented in most rice farming areas (or adjacent localities), albeit with varying levels of effort and timelines. In fact, one-third of the regions analyzed have incorporated pathogen surveillance (xenomonitoring) in mosquitoes or reservoir hosts (mosquito and/or animal screening) into their standard mosquito monitoring programs to assess WNV transmission risk to surrounding communities and to initiate early and targeted mosquito management actions.

Monitoring mosquitoes in rice fields primarily relies on the use of carbon dioxide traps, such as CDC-type and BG-Sentinel traps, which are the preferred trapping methods for native mosquitoes in Europe (ECDC, 2014; Wheeler et al., 2022). Interestingly, the mosquito species inhabiting these biotopes are common among different countries, with a predominance of five to six species (*Ae. caspius*, *Cx. pipiens*, *Cx. modestus, Cx. theileri,* and *An. maculipennis* s.l.). Overall, while *Cx. theileri* is the predominant mosquito species in southern Spain and southern Portugal along with *Cx. pipiens* and *Cx. perexiguus*, in other parts of Spain (Valencian and Catalonian rice fields), southern France, and northern Italy *Cx. perexiguus* and/or *Cx. theileri* are replaced by *Cx. modestus* (Almeida et al., 2008, 2010; Bueno Marí, 2010; Cáceres and Ruiz, 2004; Ponçon et al., 2007; Roiz et al., 2015; Severini et al., 1997) (Fig. 3). While the invasive mosquito species *Aedes albopictus* is an increasing public health problem in Europe, it is typically restricted to urban habitats (Lühken et al., 2023) and is generally not found in rice-growing areas included in this study.

The flooding cycles of the rice fields directly affect the occurrence and seasonality of certain species. For example, in Italy and Greece, where cycles of flooding and drying are constant, the proliferation of *Ae. caspius* is favoured throughout the entire cultivation season. In France, *Ae. caspius* populations occur predominantly from April to May, when the rice paddies are flooded, and gradually decrease in the following months as the flooding events reduce. Other mosquito species that require a constant volume of fresh water (*Cx. pipiens, Cx. modestus,* and *An. maculipennis* s.l.) can colonize the rice paddies only when the water stabilizes (permanently inundated fields). Their populations abruptly drop at the end of the cultivation season, when the rice fields are drained prior to harvesting. The relatively high presence of *Anopheles* spp. reported from the different countries is consistent with the available literature on rice fields (Bertola et al., 2022). In most the countries analyzed in our study, a drastic reduction of *Anopheles* vector species has been recorded in recent years (last 10–20 years) compared to historic records in rice field environments. This decline is attributed to several factors such as the increased use of phytosanitary pesticides (for the management of insect pests of agricultural relevance), changes in water quality (eutrophication), urban waste, land use (urbanization), land drainage, and crop management practices leading to the decline and/or local extinction of this genus and other related species (Bueno Marí, 2010; Chordá Olmos, 2014).

Mosquito nuisance is reported as a significant discomfort in most of the regions (Fig. S3), particularly due to *Aedes* populations. Later in the season, *Anopheles* and *Culex* mosquitoes can cause similar levels of nuisance. For both Spain (Bajo Guadalquivir) and Greece, mosquito abundance is reported to be extremely high (over 10.000 mosquitoes collected by CO_2 baited traps in 12–24 h) during the summer months (July to August) in rice paddies. In fact, the biomass of rice-field mosquitoes produced is so high that the surplus of insects collected during a surveillance program in Greece (~15 kg of mosquitoes, ca. 5 million) was successfully used for poultry feeding (Christaki et al., 2022; Tsafrakidou et al., 2024).

In terms of direct nuisance, *Ae. caspius* is probably the most important nuisance mosquito species breeding in rice fields and other floodwater habitats across Europe, imposing a significant burden to the well-being and economies of the surrounding communities. This species is a strong flyer, and adults are known to migrate long distances from their breeding sites (Bogojević et al., 2011) in search of resting habitats (vegetation) and blood meal sources. Therefore, the resulting biting pressure can affect communities well beyond rice-field environments, including urban centers kilometers away from the original breeding sites. For example, in Valencia, hotel resorts have reported mosquito nuisance as far as 25 km from potential breeding sites. In Italy, people residing near rice fields were unable to engage in outdoors activities during evening hours from May to August due to the massive occurrence of this species (Talbalaghi et al., 2002). While *Ae. caspius* plays a minor role as an arbovirus vector (Brustolin et al., 2017; Núñez et al., 2019), it is suspected to be vector of Tahyna virus and other flaviviruses (Calzolari et al., 2022; Figuerola et al., 2022).

In Europe, the mosquito species primarily involved in WNV outbreaks are *Cx. pipiens* and *Cx. modestus* (ECDC, 2023a). Both species breed in high densities in rice-field agroecosystems and have been incriminated in WNV transmission in these environments. Although these species are not known to be strong flyers, the proximity of rice agroecosystems to urban populated centers and/or the interwoven landscape of residential areas with rice farming, increases the risk of contact between these competent vectors and hosts, facilitating the propagation of a VBD outbreak under favorable environmental conditions. For example, *Cx. pipiens* has been implicated as both the enzootic and epizootic (bridge vector) of WNV outbreaks in the rice-cultivation region of Thessaloniki Greece (Chaskopoulou et al., 2013), and *Cx. modestus* has been implicated as the main amplifier of WNV in the Camargue region of southern France (Tran et al., 2017). Another rice-field mosquito species of increasing epidemiological interest is *Cx. perexiguus,* which, based on recent evidence, played a central role in the enzootic transmission of WNV in Andalusia (Spain), where its primary larval habitats are rice fields (Roiz et al., 2014; Figuerola et al., 2022). The association of rice fields with increased risk of VBD transmission is well-known, as rice fields can provide vast areas of larval habitat for competent mosquito vectors (Diuk-Wasser et al., 2007; Kovach and Kilpatrick, 2018; García-Carrasco et al., 2023). In a more recent study in California (USA), the incidence of WNV disease increased with the fraction of land under rice in each county (Kovach and Kilpatrick, 2018). However, while this was the case for California, where *Culex tarsalis* (the primary WNV vector in the region) breeds in rice fields, it did not apply to the southern US, where the dominant WNV vector, *Culex quinquefasciatus,* rarely inhabits rice-field environments. This is a great example of how rice cultivation can increase pathogen transmission risk and how local vector ecology can change the correlation between disease and land cover.

Overall, each region regardless of the country, follows a different mosquito management strategy dependent on budget availability, insecticide availability, local regulatory frameworks, resources, and expertise. Vector control activities are funded and implemented by a combination of state (national, regional) and private institutions, with the participation of consortiums and/or public agencies. In some regions, vector management programs are conducted systematically under the umbrella of a governmental, centralized, administrative unit (e.g., France, Piedmont in Italy, Greece, and Ebro-Delta in Spain) and/or control interventions are supported by city or municipality-based public health departments (e.g., Extremadura and Valencia-Spain and Veneto-Italy) following well-defined protocols. On the other hand, some locations have received interrupted attention (e.g., Piedmont, Italy) or do not control mosquitoes breeding at the rice fields (Marisma del Bajo Guadalquivir, northeastern Italy, and Portugal).

The most widely adopted method to combat mosquitoes in rice-field agroecosystems in Europe is biological larviciding with *bti*, applied primarily by air. This method is implemented routinely or under scenarios of high vector populations and/or VBD outbreaks. Previous chemical-based larviciding interventions (i.e., temphos, S-methoprene, and diflubenzuron) have been entirely replaced by biological larvicides, as the formers may have lack of specificity, short duration, and are unsafe to use, causing long-lasting harmful effects on some invertebrate aquatic life (Abe et al., 2014; Lawler, 2017). Adulticiding interventions of pyrethroid-based insecticides are conducted in urban/suburban and agricultural environments as needed, in response to high vector abundance and/or high pathogen circulation levels in vectors or sentinel animals, or under epidemic scenarios (i.e. WNV human outbreaks). These interventions include ground-level low volume (LV) surface spraying targeting the resting habitats of adult mosquitoes and ULV space spraying (by ground or air) targeting the flying, host-seeking mosquitoes. Detailed information on the precise parameters and non-target effects of aerial ULV space spray applications in Greece can be found at Chaskopoulou et al. (2011a, 2014).

Other biological control methods have been applied in a limited number of cases without continuity, as they proved to be inefficient, or difficult to implement, such as rice-fish system (a practice that integrates rice farming with aquaculture) (Allgeier et al., 2019), or water level manipulation. The use of the film Aquatain as a mechanical control method in rice fields has been also proposed (Bukhari et al., 2011) but negative impact of non-target fauna has not been studied. Another alternatives is the use of mosquito collection trap barriers surrounding human-inhabited areas, which demonstrated a 30–70% reduction in nuisance (Poulin et al., 2017; Pontifes et al., 2024). Complete elimination of the habitat is not a feasible solution, as it would result in negative consequences for the local agricultural economy and adverse environmental impacts (Toral and Figuerola, 2010).

While detailed examples of mosquito control programs in Europe are scarce, experiences from other countries, particularly those targeting malaria vectors, have shown successful approaches to mitigate mosquito populations in rice-field agroecosystems. For instance, new irrigation strategies, such as intermittent submerged irrigation and/or wet irrigation, have been widely applied in China with promising results (Zhao and Xue, 2022). These systems might be also used to apply *bti* through drip irrigation systems. Additionally, several examples in China (Chan et al., 2022) and USA (Wheeler et al., 2022) report on mosquito population reductions of ca. 70–99% through fish cultivation (rice-fish coculture methods), an approach that also contributes to increased rice production (Zhao and Xue, 2022). However, the application of *Azolla* aquatic fern in China, while showing potential for mosquito control in rice paddies, has had negative impacts on biodiversity due to its invasive nature (Garcia-Murillo et al., 2007). In the United States, aerial ULV adulticide treatments (i.e. pyrethroids) in the rice field region of California successfully interrupted WNV transmission, reducing mosquito infection rates post-treatment and human cases (which were six times higher in untreated areas) (Carney et al., 2008). In the United States, mosquito control is not only limited to biological control but is integrated into a comprehensive Integrated Vector Management (IVM) strategy, which combines surveillance, environmental management, biological and chemical control methods, and public outreach. Farmers are directly involved in vector control operations, playing a key role in these efforts (Wheeler et al., 2022). Implementing such IVM programs in European rice-field agroecosystems, which combine a diverse array of approaches (biological, chemical), will allow for a cost-effective and environmentally sustainable solution. However, for this scenario to be feasible, the European regulatory framework needs to be adjusted and harmonized across different countries to facilitate the use of new biological control tools (e.g., larvivorous fish) or the management of existing ones. This would also support the application of evidence-based, targeted chemical interventions.

Irrigation practices play a critical role in determining the extent of mosquito production and, consequently, the risk of VBDs (Kovach and Kilpatrick, 2024). By adopting water-efficient and environmentally sustainable irrigation methods, such as intermittent flooding, farmers can significantly reduce mosquito breeding while maintaining or even enhancing crop yields. Integrating these practices with comprehensive IVM strategies can further mitigate public health risks and promote a more sustainable agricultural system.

5. Conclusions

The compromise between agricultural productivity and public health underscores the importance of holistic approaches to rice cultivation and mosquito control, ensuring both food security and healthier communities. Effective management of mosquito populations in these environments necessitates a One Health approach, which involves collaboration among farmers, vector control operators, public health professionals, and the scientific community. Farmers require guidance on optimizing agricultural practices to minimize mosquito production, such as adjusting irrigation schedules to disrupt mosquito breeding cycles. Vector control operators and public health professionals must work together to implement and monitor cost-effective and sustainable interventions that do not negatively affect agricultural productivity or ecosystem health. Meanwhile, the scientific community plays a critical role in enhancing current knowledge on these practices and in developing innovative strategies and technologies to mitigate mosquito proliferation. This integrated approach ensures that health risks are minimized without compromising food security, thereby providing sustainable and long-term solutions to the interconnected challenges of agriculture and public health. Given the increasing risk of WNV in the European Mediterranean, concerted efforts and cooperation among countries are imperative. In the context of a changing climate, the emergence of VBD in previously unaffected regions, such as Europe, underscores the critical need for ongoing surveillance and proactive management of future and already emerging threats.

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CRediT authorship contribution statement

Mikel A. González: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alexandra Chaskopoulou:** Writing – original draft, Validation, Supervision, Investigation. **Loukas Georgiou:** Validation, Supervision. **Eva Frontera:** Writing – review & editing, Supervision, Investigation. **Francisco Cáceres:** Writing – review & editing, Investigation. **Montse Masia:** Methodology, Investigation. **Raquel Gutiérrez-Climente:** Formal analysis, Conceptualization. **Gregory L' Ambert:** Writing – review & editing, Investigation, Formal analysis. **Hugo Osório:** Writing – review & editing, Investigation. **Gonçalo Seixas:** Writing – review & editing, Investigation. **Francesco Defilippo:** Methodology, Investigation. **Mattia Calzolari:** Supervision, Investigation. **Fabrizio Montarsi:** Investigation, Formal analysis. **Andrea Mosca:** Writing – review & editing, Methodology, Investigation. **Jordi Figuerola:** Writing – review & editing, Resources, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jordi Figuerola reports financial support was provided by LaCaixa Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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