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Using detection dogs to reveal illegal pesticide poisoning of raptors in Hungary

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Abstract. In Hungary, during the 2000s, pesticide poisoning became the most important threat for raptors, especially for the globally threatened Eastern imperial eagle (*Aquila heliaca*). In September 2013, with a focus on carbofuran and phorate, the first poison and carcass detection dog (PCDD) unit was formed in Hungary with a specifically trained detection dog and handler. Two more dogs were subsequently trained and joined the unit in 2017 and 2020 respectively. Between its inception until August 2020, the PCDD unit conducted 1,083 searches in five countries, which revealed 329 poisoned animals of 15 bird and nine mammal species, 120 poisoned baits and five pesticide products. Globally threatened species, including eight Eastern imperial eagles and four saker falcons (*Falco cherrug*), were among the detected victims. Present at 66.45% of wildlife poisoning events, the unit revealed 37.87% of the victims and 79.70% of the poisoned baits known in Hungary during the period 2013-2020. Compared to human surveys, the PCDD unit demonstrated a significantly higher find rate for poisoned baits. At 22 poisoning events (14.38% of all cases) only the PCDD unit revealed victims or poisoned baits; cases that would probably have gone undetected without the PCCD unit. Of the two focal pesticides, carbofuran was more frequently detected – in 88.56% of the positive samples. The unit played a significant role in detecting and combating wildlife poisoning incidents by deterring potential offenders and facilitating police investigations through retrieval of evidence otherwise difficult to obtain.

Key words: avian poisoning, canine, carbofuran, insecticide, phorate, raptor, rodenticide

Introduction

Intentional or accidental poisoning of wildlife causes significant mortality of protected vertebrate species worldwide (Richards 2012, Ogada 2014, Brochet et al. 2019, Plaza et al. 2019). Pesticides are typically most commonly associated with wildlife poisoning incidents, primarily through accidental misuse in agriculture (Berny 2007) or intentionally prepared poisoned baits (Márquez et al. 2013, Chiari et al. 2017).

Accidental poisoning usually occurs when bait stations are improperly installed and/or legally banned pesticides are used in agriculture, resulting in poisoned carcass availability for predators or predisposing exposed, debilitated animals (e.g. rodents, insects) to predation through abnormal, conspicuous behaviours (Sánchez et al. 2012, Nakayama et al. 2018). Nontarget herbivorous organisms may also be harmfully exposed to pesticides. Depending on the substance and degree of exposure, predators and/or scavenging species can be secondarily or even tertiarily poisoned (Lehel et al. 2010, Krone et al. 2017, Shiao-Yu et al. 2018).

In contrast, the intentional use of poisoned baits as a tool to directly control mammal or avian predator species is also widespread (Mineau et al.

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1999, Glen et al. 2007, Guitart et al. 2010). Although in European countries it is illegal to intentionally poison wildlife in natural habitats, pesticides are nonetheless still used against the most common predator or scavenging species (mostly carnivores and corvids), but also causing significant mortality in protected bird and mammal species (Giorgi & Mengozzi 2011, De Roma et al. 2018, Ntemiri et al. 2018). Raptors are especially affected by poisoning events due to their foraging habits and high dispersal capacity, which has resulted in adverse effects at the population level for several threatened species (Hernández & Margalida 2008, 2009, Mateo-Tomás et al. 2020).

In Hungary, the poisoning of raptors has been reported with increasing intensity since 2000 (Sályi et al. 2005, Bedő 2012, Deák et al. 2020a). An especially high prevalence was detected for the globally threatened Eastern imperial eagle (*Aquila heliaca*), where poisoning became the primary cause of mortality and threatened to undermine previously favourable population trends for the species (Horváth et al. 2011, Deák et al. 2020b).

Detecting illegal poisoning events *in situ* is challenging and perpetrators are rarely prosecuted due to a lack of clear, conclusive evidence. In Europe, forensic and police investigations into such cases were greatly facilitated after detection dogs were successfully implemented to locate poisoned baits and carcasses in Spain and Italy (Fajardo et al. 2012, LIFE ANTIDOTO 2014, de la Bodega Zugasti 2016).

Building on the work done in these countries, the first poison and carcass detection dog and handler were trained in Hungary in 2013 (Horváth et al. 2018). Here, we summarize the results obtained by this first specialized Central European unit between 2013 and 2020.

Material and Methods

Dog training

The training method used for the poison detection dogs was conducted by the Service Dog Training Centre of the Hungarian Police (Dunakeszi) with the technical help of MME (Magyar Madártani és Természetvédelmi Egyesület/Birdlife Hungary). The initial intensive training lasted for four months, between April and August 2013. As a first step, fifteen 10-month-old German shepherd dogs from a kennel breeding specialised working dogs (Karancslapujtő, Hungary) were assessed. The assessment included both indoor and outdoor exercises, such as searching (e.g. a hidden ball or toy), walking down to a dark cellar, walking on raised structures, and exposure to the discharge of a firearm. The trainers at the Centre selected the two dogs deemed best qualified. Based on their performance during the first month of the training, a dog named "Falco" (born May 2012) was selected to receive the specialized poison and carcass detection training (Fig. S1a), while the other dog was retained by the police for different training purposes.

Poison detection training was conducted in a manner similar to that developed for drug-detection dogs by the Centre since 1978: dogs were motivated through reward with ball-games. Food rewards (i.e. treats) were never used since ingestion of even a small portion of a poisoned bait could be lethal to the dogs and, therefore, any positive link between the work and food was avoided. For similar reasons, the dogs were fed on an extremely strict diet, where only high-quality dry food was provided on a daily basis.

The dogs were trained to detect the scents of: 1) decomposing carcasses (several species of birds and mammals in different stages of decomposition), 2) carbofuran (from the liquid pesticide product Chinofur 40FW), and 3) phorate (from the granular pesticide product Thimet 10G).

Carbofuran and phorate (both banned in the European Union) were selected for training as the two pesticides most commonly implicated in intoxication of protected bird species in Hungary (Sályi et al. 2005, Horváth et al. 2008, Bedő 2012). MME obtained special permission from the National Food Chain Safety Office for the possession and use of each pesticide strictly for the purposes of detection dog training. Scent samples were prepared for the training by putting 2-4 ml of liquid pesticide (in case of carbofuran) or 2-4 g of granular pesticide (in case of phorate) inside a piece of cotton wool. The wool was put in a closed but perforated plastic tube in order to avoid the possibility of direct contact, but enabling scent detection. The unused poison substances were stored in a closed container and were always handled with protective gloves, while the behaviour of the dogs was continuously monitored when working with pesticides in order to avoid the possibility of any accidents (i.e. any direct contact with the pesticide) that could cause intoxication of the human handler or the dogs. Dogs were specifically trained not to touch either any carcasses or baits, but to give barking signals if they were ca. 50 cm from the source of the scent.

After the four-month training period, on 9 August 2013, both the dog and handler passed the police-certified poison and carcass detection assessment. This date marks the official foundation of the first Hungarian poison and carcass detection dog (PCDD) unit. The PCDD unit initiated field operations in late August 2013. Since this first training period, the PCDD unit has continued to participate in one-month follow-up training and has taken the assessment annually to maintain the official police qualification.

In September 2017, a Belgian shepherd named "Carlo", born August 2016 (Fig. S1b) joined the PCDD unit after successfully undergoing training and assessment equivalent to Falco. A third dog, named "Hella" (German shepherd, born June 2018), started the same course in December 2019 and executed a little interim fieldwork within a training framework in 2020 – its official assessment having been delayed to December 2020 due to the COVID-19 pandemic.

Working protocol

PCDD unit operations covered all of Hungary with assistance from the Hungarian Anti-Poisoning Working Group, which was founded in the framework of the Hungarian Raptor Conservation Council in 2013 (Horváth et al. 2016). The working group consists of all ten Hungarian national park directorates and all relevant conservation NGOs working in raptor conservation and against wildlife poisoning. In parallel with the foundation of the unit, the PCDD handler was nominated as the national coordinator of the working group. A standardised protocol was adopted by the working group that defines the main procedure in case of a suspected poisoning event for all 250 members of the Hungarian ranger network and several hundred active data providers of the NGOs. In this way, the PCDD unit was regularly informed as soon as a wildlife poisoning case was suspected by conservationists on Hungarian territory. The unit also operated a national Bird Crime Hotline, but in our experience, only a few sporadic reports came from the public compared to the notifications received from the professional working group.

Beside the Hungarian cases, the PCDD unit occasionally also undertook searches in neighbouring countries by official invitation of local police authorities (Austria, Slovakia and the Czech Republic) and conservation organizations (Serbia). The required veterinary health checks and valid dog-passports were arranged for all cross-border transport and foreign work.

Types of search

Six main types of searches were conducted by the PCDD unit, according to the source of information and the aim of the search: 1) Active report – field searches near the time of recent (i.e. less than one month before the search) mortality or recovery (i.e. injured or debilitated, living animals) of predators, when the possibility of poisoning cannot be excluded. Such cases were reported to the PCDD unit by the national park ranger service, MME employees and volunteers or local residents. The events were usually reported to the PCDD unit immediately and field searches were typically executed within 1-7 (generally 1-3) days after discovery. The aims of these surveys were primarily to a) locate intoxicated animals and related samples for pathological investigations or veterinarian care, b) locate poisoned baits or other sources of poisoning for removal to prevent further mortality, and c) facilitate ongoing police investigations; 2) Archive location – field searches at sites where previous probable illegal poisoning of predators occurred (i.e. 1-60 months before), in order to verify if previously identified illegal activities were ongoing; 3) Bird-tracking alarm – MME and other conservation or research organizations requested assistance from the PCDD unit if a GPS-tagged bird behaved abnormally or the tags stopped transmitting, in order to find the bird and/or GPS-tag and try to determine the cause of mortality or injury; 4) Random location – field searches at sites where illegal persecution cases had not previously been recorded (i.e. in the last 60 months), but if they did occur, could cause significant conservation problems. These surveys were primarily focusing on Special Protection Areas (SPAs) of the EU's Natura 2000 network, especially where breeding territories of Eastern imperial eagles occurred or possible persecution cases were suspected due to indirect information (e.g. sudden disappearance of monitored raptor breeding pairs, anecdotal information about frequent mortality of predators); 5) Search warrants – the police invited the PCDD unit to assist them in executing search warrants, if investigations revealed any suspicious property (enclosed building or semi-open yards) of probable perpetrators where there was a high chance of finding poisoning substances or other evidence of illegal persecution of raptors; 6) Other specific surveys – the PCDD unit were also occasionally invited to participate in field surveys to test the efficiency of detection dogs in related conservation problems/projects/applications, such as surveying for avian electrocutions (i.e. carcass search), for scats of grey wolfs (*Canis lupus*), for active dens of steppe polecats (*Mustela eversmanii*), or to detect mortality of vertebrates caused by mowing in farmlands (Deák et al. 2020).

Search methodology

Field searches were planned in advance based on the available background information and analysis of satellite images. The dogs were transported in a crate to and between search locations in a 4WD vehicle. A given survey was always started at the location considered to offer the highest chance of finding evidence (i.e. the locations of reported carcasses, baits or the last GPS signals of disappeared satellite-tracked birds). If raptors or corvids were the presumed primary targets (e.g. poisoned baits placed in the middle of open fields) or agricultural misuse of pesticides was suspected, the survey was more focused on open habitats and edges (Fig. 1a). If mammals were thought to be the intended targets (e.g. baits hidden under vegetation or soil), then dense woodland, bushes and surroundings of nearby dens were investigated more thoroughly (Fig. 1b). The surroundings of the nearby properties of possible suspects (e.g. pheasant or poultry farms, hunting infrastructures, etc.) were also searched intensively in most cases.

Field searches were conducted with the handler working the dog off-leash. The PCDDs indicated a find with loud barking, which was especially useful when dense vegetation obscured the handler's vision. PCDDs wore canine GPS-collar systems (Garmin Astro 320 Handheld and T5 Dog Device) and a collar bell during surveys, providing the handler with real-time feedback on the dog's current position, and yielded recorded tracklogs for both the PCDD and the dog handler. Regardless, the handler kept almost continuous visual contact with the dog and as soon as the dog was not visible for more than ca. 15-30 seconds and/or was further than ca. 40 meters, the handler gave signals for the dog to return in order to assure the dog's safety. The location and details of all findings of the PCDD unit, i.e. carcasses or living, intoxicated animals, possible bait material and all other potential evidence which could be related to a wildlife crime case (e.g. footprints, plastic gloves) were registered in a field GIS system (OruxMaps or AlpineQuest). Most of the unit finds were made by the PCDDs themselves, although in some cases the handler also located more obvious evidence (i.e. larger or well visible carcasses). This rarely happened before the dog could detect them. However, we did not differentiate between such cases and simply attributed all discoveries to the PCDD unit. If the results of the field survey suggested it could be a wildlife crime case, the police was immediately notified by the responsible ranger or the handler and an official crime scene investigation could then be conducted (Fig. S2a). In the event of a suspected wildlife crime, the carcasses and poisoned baits found during the searches were transferred to the Laboratory for the Pathology of Mammals, Wildlife and Poultry of the National Food Chain Safety Office in Budapest, where the pathological and toxicological analyses were undertaken. The chain of evidence was ensured by carcasses individually labelled by the ranger service (according to Horváth et al. 2016) and by transportation bags sealed by the police.

When a search warrant was being executed, the police and dog handler conducted an initial site assessment to see if any threats were present for the dogs (other dogs, harmful objects, scent, which could derive from potentially dangerous aerial concentration of poisonous substances etc.). If the premises were secured and the search was planned inside a building, the handler closed doors and windows to avoid drafts and to help scent-localisation before getting the PCDD out to work. The search warrants were executed from room to room, including all parts of the premises and the yard. The dogs started the search in a particular room or part of the building independently without a leash. If the dog did not find anything in a given room, the search was repeated with the direction of the handler, who one by one pointed to the main objects in the room, which were investigated thoroughly again by the dog. If the dog gave their bark alert, members of the police were on hand to immediately step in and investigate whether any evidence could be found at the given location.

Data analysis

The data from all detected wildlife poisoning and bird crime cases of the Hungarian Anti-Poisoning Working Group were incorporated in a national

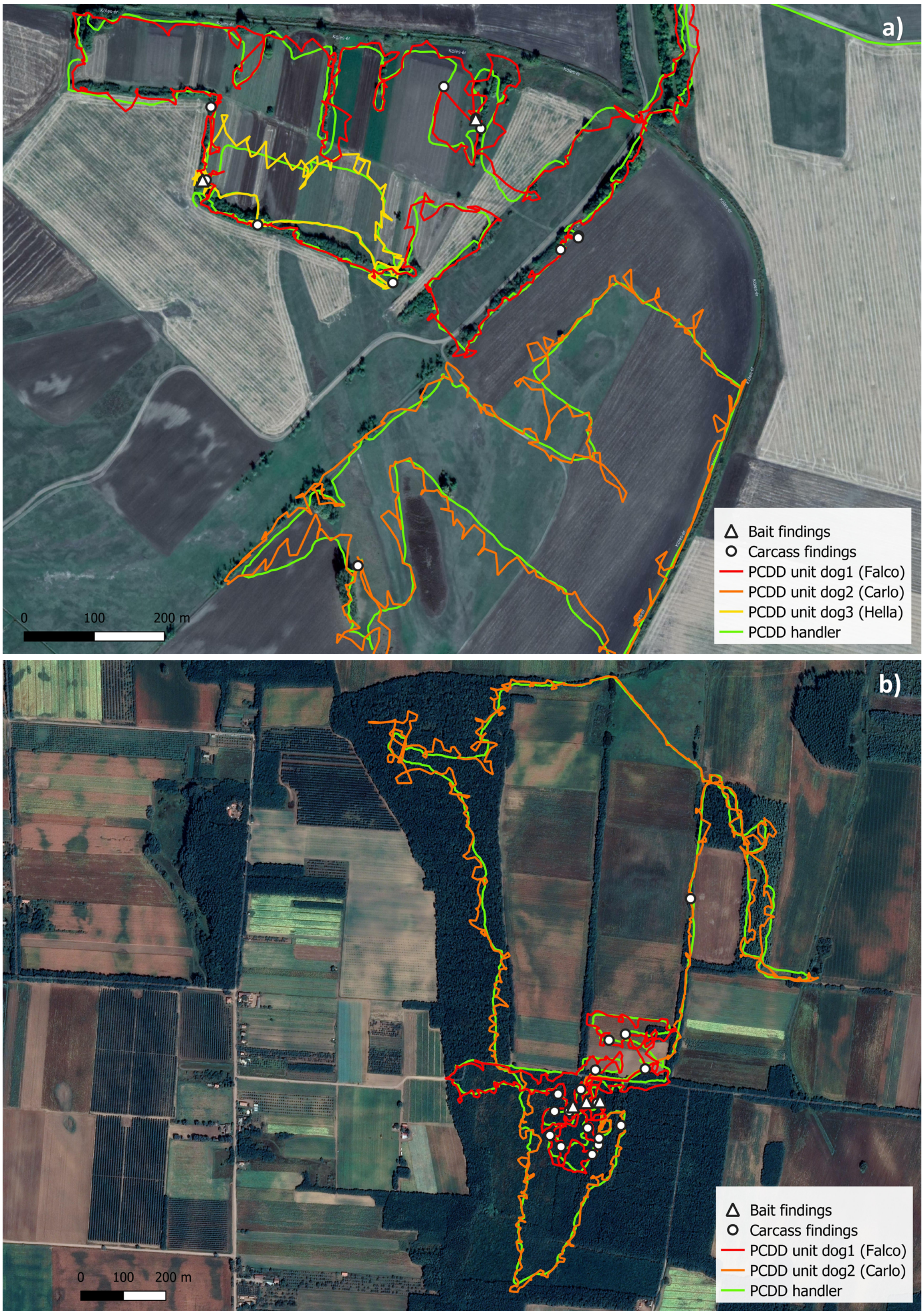

Fig. 1. Typical geographical coverage of field searches of the PCDD unit: a) poisoned baits were directly available to raptors, therefore the search concentrated on open habitat and edges (Bihartorda, Hungary, March 2020); b) poisoned baits were hidden and primarily targeting mammals, therefore searches focused on woodland habitat (Újfehértó, Hungary, March 2020).

Bird Crime Database. The database enabled the comparison of findings made by the PCDD unit with other poisoning cases where the unit was not involved. We included all the following cases among poisoning events and findings according to the categorization of the database (Deák & Horváth 2018): a) illegal poisoning – a legally banned pesticide was detected in carcasses by laboratory analyses and/or poisoned bait was used against predators; b) accidental poisoning – legally authorized pesticide was detected in carcasses by laboratory analyses; c) suspected poisoning –

symptoms and field circumstances showed clear signs of pesticide poisoning (e.g. several carcasses close to each other, dead insects around the carcass), but laboratory analyses did not yield residues or were not conducted, mostly due to the advanced state of decomposition of a sample.

Field findings were grouped into "poisoning events", if the intoxicated specimens or baits were found close to each other in space (i.e. within a 3 km radius circle) and time (i.e. estimated date of mortality within one month) and the same type of pesticide was detected. The date of the first finding classified to the given poisoning event was used as the starting date of the event for seasonal analyses.

The QGIS 3.10 software (QGIS Development Team 2019) was used for mapping and analysing spatial data. The R software, version 3.5.2 (R Core Team 2018), was used for statistical analyses. McNemar's exact test in the R package exact2×2 (Fay 2010) was performed to evaluate bait detection odds by the PCDD unit in comparison with human surveyors. The test compared the proportions of events where baits were found by both, neither or one of the two methods.

Results

Coverage and overall results of surveys

A total number of 1,083 surveys have been conducted by the PCDD unit during the 85 months since its inception (August 2013-2020). The field surveys usually covered 1-7 km (min-max: 0.2-20 km) and lasted for 1-3 hours (min-max: 0.25-8 hours) depending on the terrain, weather, logistics and frequency of findings. The total length of tracks covered by the handler during the field searches exceeded 4,000 km (Fig. S3). The PCDDs usually logged a distance 2-4× greater than the handler due to the off-leash searching method used.

The unit found 329 poisoned animals, 120 poisoned baits and five poisonous substances (i.e. pure pesticide products) in total (Table S1). Chicken eggs, whole carcasses of smaller bird or mammal species and viscera of larger mammals were also used as baits for poisoning (Fig. S2b). Poisoned specimens were detected during 90 searches (mean number per search ± SD = 4.65 ± 4.94), while baits or substances were found in 38 searches (mean number per search ± SD = 3.21 ± 3.67). The detection rate (i.e. the number of surveys when finds were made divided by the total number

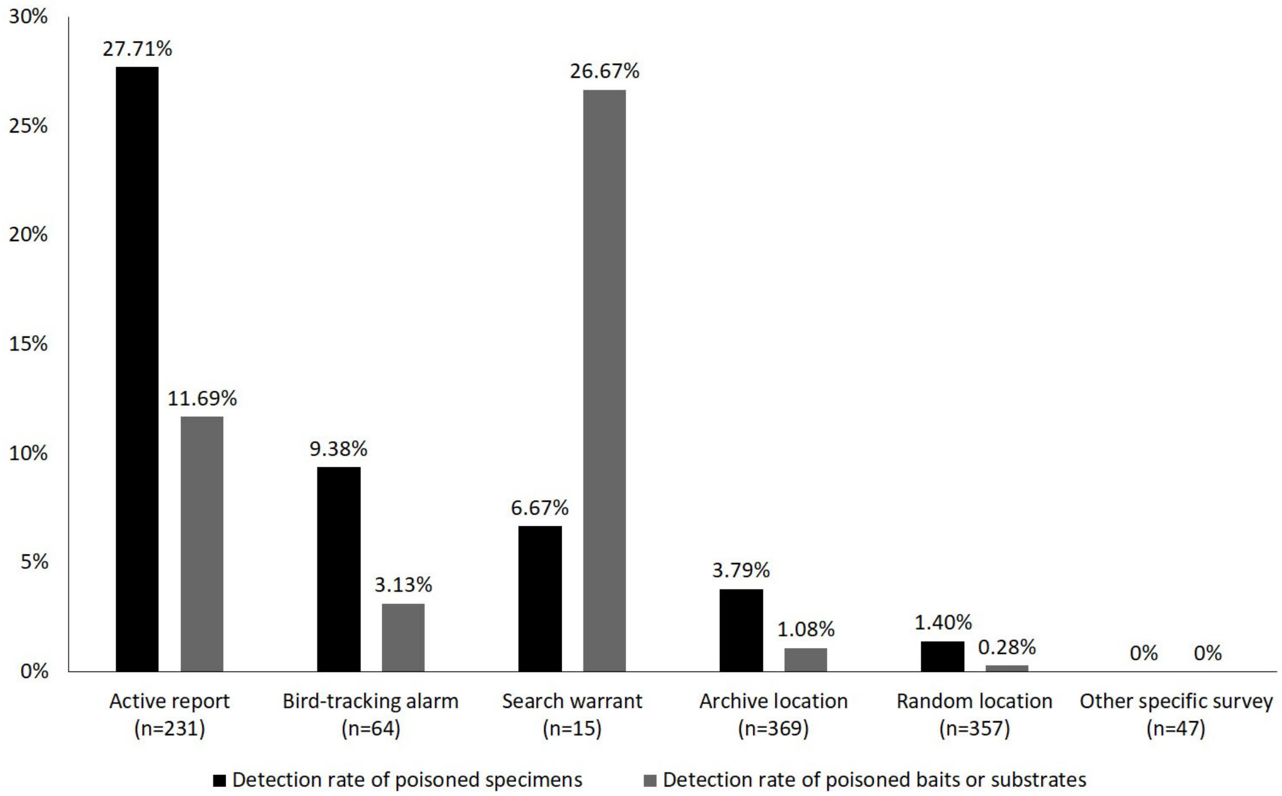

Fig. 2. The detection rate (i.e. the number of surveys when a find was made divided by the total number of surveys) of poisoned animals and poisoned baits or substances among different types of PCDD unit searches (n = 1,083).

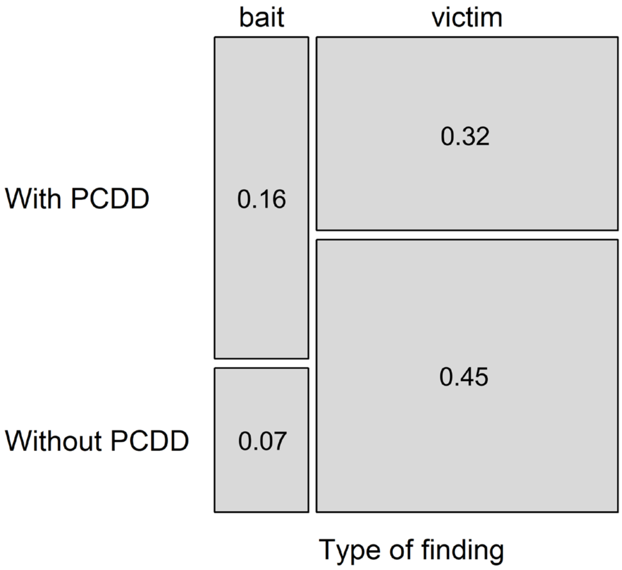

Fig. 3. Mosaic plot showing the relative frequencies of finding poisoned victims or poisoned baits by the PCDD unit or by solely human search teams of rangers or conservationists in those poisoning cases, when scenes were surveyed with both methods (n = 91).

of surveys) was 8.31% for poisoned animal findings, and 3.51% for poisoned bait or substance findings, but the rates differed greatly according to the type of search undertaken (Fig. 2). "Active report" searches yielded the highest proportion of poisoned specimens, while "search warrant" searches were associated with the highest poisoned bait or substances find rates.

The three PCDDs were employed for different periods and with different frequency. Falco undertook 893 searches and made 392 finds related to pesticide poisoning (victims and baits together). Carlo undertook 177 searches with 61 recorded finds, while Hella participated in 13 searches and found one victim of poisoning.

The field searches of the PCDD unit were connected to 101 different poisoning events in Hungary. During the timeframe of the unit's deployment, a total of 152 reported poisoning events involving 787 recorded victims and 133 poisoned baits in Hungary were recorded (Hungarian Bird Crime Database, unpublished data). This means that the PCDD unit executed field searches at 66.45% of all known events and revealed 37.87% of the victims and 79.70% of the poisoned baits in Hungary. Moreover, in 22 instances of suspected

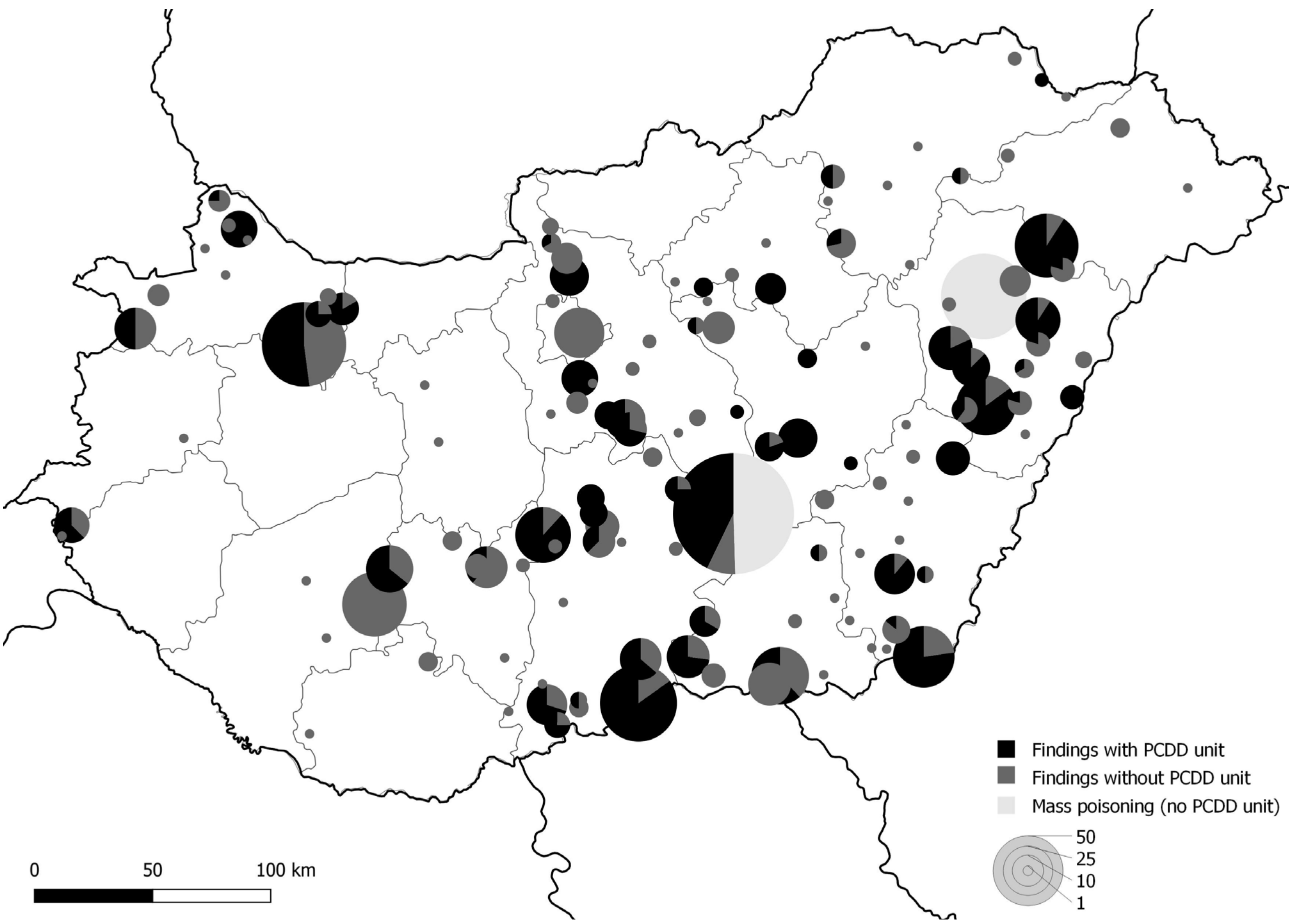

Fig. 4. Distribution of pesticide poisoning findings with and without the PCDD unit in Hungary between August 2013 and August 2020 (n = 917).

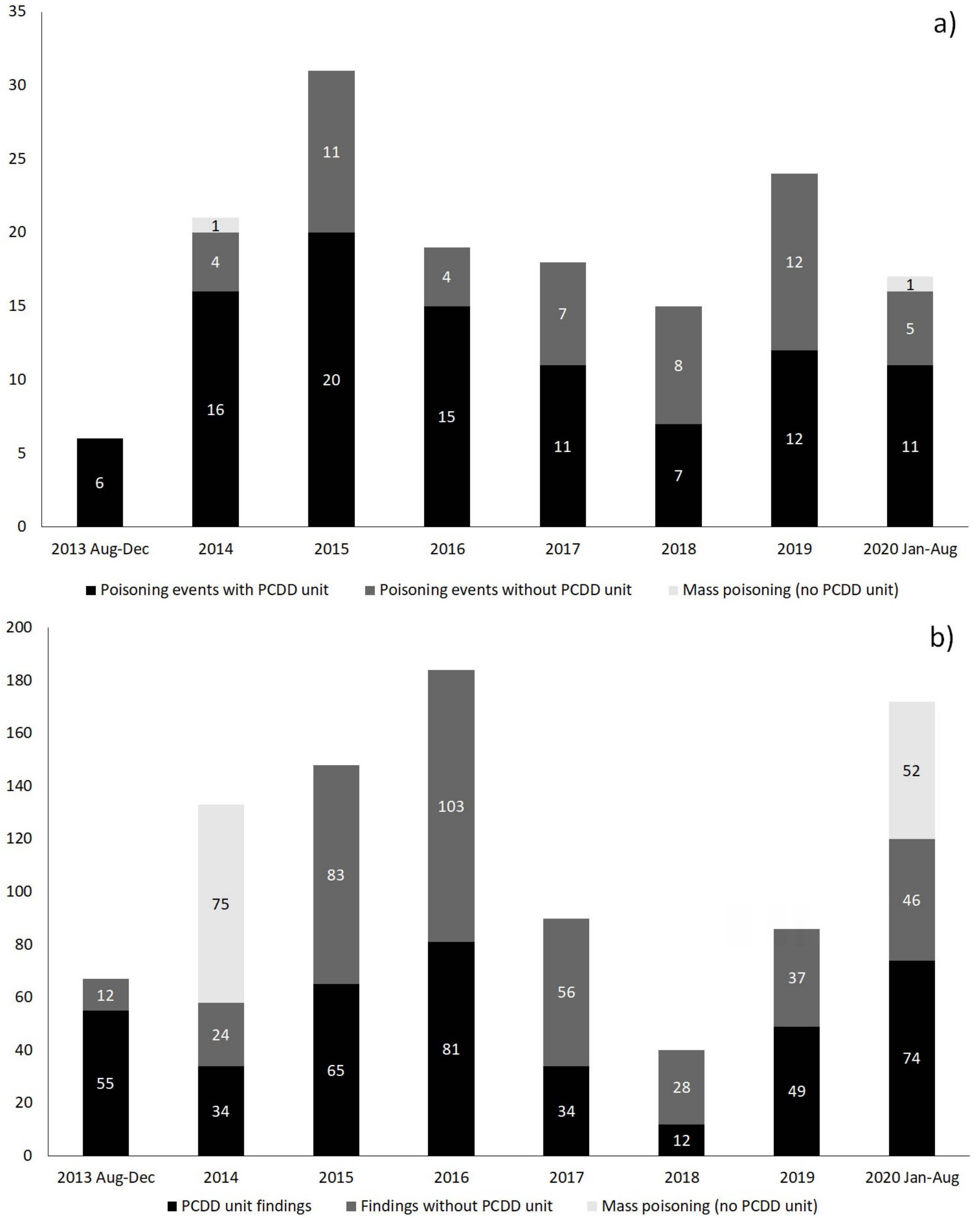

Fig. 5. Annual distribution of (a) investigated independent poisoning events (n = 152) and (b) poisoned specimens and baits found in the field (n = 920) with and without the PCDD unit in Hungary between August 2013 and August 2020.

poisoning (14.38% of all cases) only the PCDD unit revealed victims or poisoned baits, therefore these cases would probably otherwise have gone unnoticed or it would not be possible to proceed with the investigation. Additionally, the PCDD unit was significantly more likely to find poisoned baits than teams consisting only of rangers or conservationists in those poisoning cases, when scenes were surveyed with both methods (n = 91, OR = 4.2, 95% CI: 1.54-4.26, $P < 0.005$; Fig. 3).

Although the detected poisoning events were geographically distributed across all of Hungary, they showed clear concentration towards open agricultural areas of the Hungarian Plain (Fig. 4). Two single-species mass poisoning events were not investigated by the PCDD unit, although they represented a significant proportion of

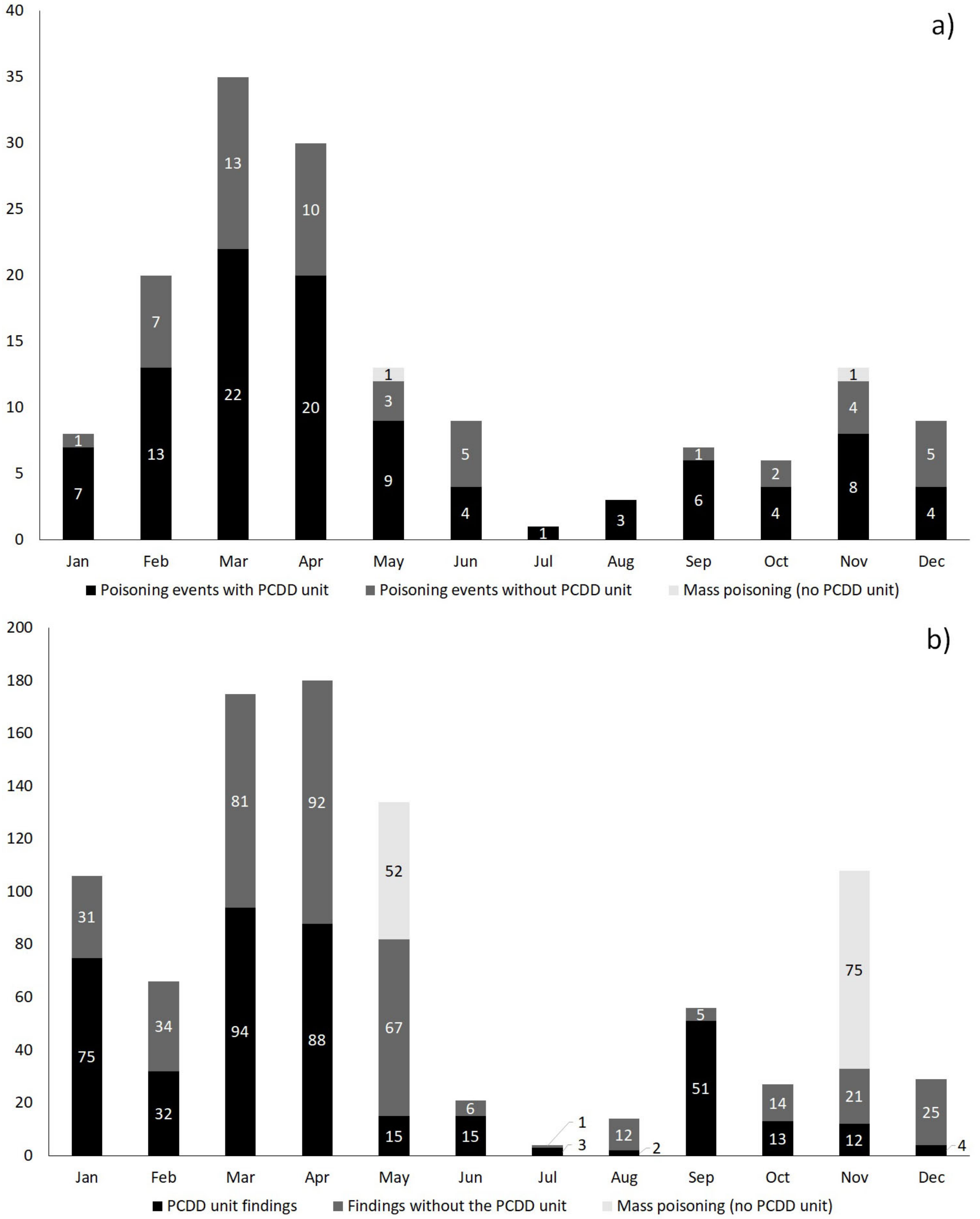

Fig. 6. Monthly distribution of (a) investigated independent poisoning events (n = 152) and (b) poisoned specimens and baits found in the field (n = 920) with and without the PCDD unit in Hungary between August 2013 and August 2020.

mass mortality encountered during the search timeframe. Resulting in 75 common crane (*Grus grus*) mortalities in November 2014 and 52 European pond turtles (*Emys orbicularis*) mortalities in May 2020 respectively, these events are indicated separately in the figures.

Affected species, baits and substances used for poisoning

The PCDD unit found poisoned specimens of 15 bird and nine mammal species, nine different types of poisoned baits and the two types of pesticide products which they were trained to detect (Table S2). The victims represented 13 nationally protected and two globally threatened species, including eight Eastern imperial eagles and four saker falcons (*Falco cherrug*). No living, intoxicated animals were found by the unit.

Although the PCDDs were only trained to detect carbofuran and phorate, subsequent laboratory testing of carcasses and especially baits revealed the presence of seven types of pesticides (Table S3). The most frequently identified pesticides were carbamates (carbofuran and methomyl), and carbofuran alone was detected in 88.56% of the positive samples. Organophosphate insecticides (phorate, terbufos and diazinon) were detected in 9.15%, while anticoagulant rodenticides (warfarin and brodifacoum) were seen in 2.94%. The exact source of poisoning was frequently not revealed, but among those cases when the sources of pesticides could be identified, carbamate and organophosphate insecticides were found to be used primarily for poisoned baits against predators, while anticoagulant rodenticides caused secondary poisoning, mostly through agricultural misuse. The agricultural use of all pesticides detected from the carcasses and baits are banned in Hungary and in the neighbouring countries where searches with the unit took place.

Seasonality of revealed poisoning cases

There was no continuous annual trend in the number of detected poisoning events or findings (Fig. 5). The first few years of the work (2013-2015) showed an increasing trend in events, followed by a decrease (2016-2018) and an increase again till the end of the period (2019-2020).

On the other hand, seasonal patterns were observed, as the majority of poisoning cases happened in late winter and early spring (February-April), while least activity was detected in mid-summer (July) (Fig. 6). The early spring peak of poisoning events clearly coincide with the peak season of predator control activities by hunting organizations. Rural dirt roads usually became more easily passable during this period following winter conditions, which facilitated the movements of both the perpetrators and surveyors in more remote areas.

Search warrants

Altogether, 15 search warrants were executed by the PCDD unit in association with eight different police investigations in four countries. Evidence for bird persecution crimes were revealed with the help of the unit in four of the search warrants (26.67%) connected to four separate police investigations (50%). In one further case the PCDD unit was involved in a search warrant, but the police found conclusive evidence of wildlife crime (illegal taxidermy mounts of raptors) before the unit could start the operation. Four suspects were hunters and one was a poultry-keeper and they were all suspected of the use of poisoned baits to illegally control predator species.

If search warrants were ordered immediately after finding evidence in the field (as in one investigation in Hungary) or prior to the interrogation or prosecution of the suspects (one investigation in Hungary, Austria and Czech Republic and two in Slovakia) a high success rate (83.33%) was achieved, as pieces of evidence for bird persecution were revealed in five out of the six investigations. On the other hand, evidence did not come to light – as was foreseen – when the search warrants were preceded by interrogation or prosecution of the suspects (two investigations in Hungary).

Other opportunistically detected wildlife crime cases

Field searches of the PCDD unit also revealed 21 findings related to other types of wildlife crime cases. As the PCDDs were trained to sniff out all types of vertebrate carcasses, the unit has also proven effective in helping to uncover carcasses not related to poisoning but which, upon forensic examination, have shown other causes of death instead. Illegal shooting was detected in 11 cases affecting seven common buzzards (*Buteo buteo*), two northern goshawks (*Accipiter gentilis*), two common ravens (*Corvus corax*) and one grey wolf. One European wildcat (*Felis silvestris*) was found to have been killed by hounds in an illegal hunt. Illegal installation of coil spring traps was detected in five cases, while illegally managed ladder traps were observed to cause the death of two common kestrels (*Falco tinnunculus*). The PCDDs could help reveal illegal trapping by the scents of dead or living animals even in well-hidden traps, but larger and well-visible traps were also found by the handler during the surveys. Illegal nest destruction was detected by the scent of decomposing eggs or chicks among the collapsed nest material in two cases. This resulted in the breeding failure of one Eastern imperial eagle and one common raven pair.

Discussion

Our results have shown that the PCDD unit played an important role in the detection of vertebrate pesticide poisoning events in Hungary since its inception. Comprising 1-3 dogs and handler, this single unit increased the number of detected poisoned victims and, especially of poisoned baits, for the whole country. The PCDD unit also assisted in the first successful search warrants executed in wildlife poisoning cases in four Central-European countries. The findings of the unit greatly facilitated the number and efficiency of police investigations, and significantly increased the chances of prosecution in wildlife poisoning cases. The high prevalence of nationally protected and even globally threatened species highlights the conservation relevance of pesticide poisoning in Central Europe, as these species are already struggling and poisoning further harms their populations.

Theoretically, perpetrators committing illegal poisoning could be sentenced under four different crime charges according to the Hungarian Criminal Code. These could include criminal offenses with toxic substances (188 §), damaging the natural environment (242 §), cruelty to animals (244 §), and poaching game (245 §). In practice, there were no convictions in wildlife poisoning cases in Hungary between 2008 and 2014, but seven offenders in five prosecution cases were convicted in 2015-2016 (Horváth et al. 2018).

Besides these concrete findings, the presence of the PCDD unit was a deterrent to possible offenders, an effect multiplied with the help of numerous media reports, presentations at stakeholder workshops and other direct conservation actions of the HELICON and PannonEagle LIFE Nature project. It is thought that all these actions have helped to reduce poisoning incidents which were directly affecting Eastern imperial eagles and that their population is starting to increase again after a few years of stagnation (Horváth et al. 2018).

Although the PCDDs were only trained to detect carbofuran and phorate, subsequent laboratory analysis of bait materials and carcasses found by the dogs revealed the use of additional illegally used pesticides. Regardless, our results highlighted that carbofuran is still the most frequently used and most hazardous pesticide for predators in Hungary, a situation similar to elsewhere in Central Europe and other parts of the world (Poledníková et al. 2010, Richards 2012). Phorate was also detected in 26 cases. This chemical has also caused significant conservation problems worldwide (Elliott et al. 1997, Kalaivanan et al. 2011). Although all pesticides containing carbofuran or phorate were banned for agricultural use in Hungary long before the PCDD unit was conceived (in 2007 and 2005 respectively), significant illegal stocks remain and illegal trade from neighbouring countries is presumed.

We believe that the parallel training method of PCDD dogs, which focused both on the scents of carcasses and the most commonly used pesticides, was an important component for their success. On the one hand, the scent of decomposing carcasses was the primary stimulus that helped the location of mortalities in the field sometimes from great distances, even up to 100 m. On the other hand, the ability to detect the substance itself was the main stimulus during indoor searches (i.e. search warrants) and probably also facilitated the effective detection of a size range of poisoned baits in the field, including very small pieces.

The increased detection of anticoagulant rodenticide – especially bromadiolone and brodifacoum – poisonings in Hungary is also worrying (Fazekas et al. 2018). Brodifacoum and warfarin were also detected in some of the samples located by the PCDD unit. The outdoor agricultural usage of such rodenticides is also banned in Hungary, but recently farmers seem to be using them with increased frequency, which has also been implicated in significant mortalities of Eastern imperial eagles (Deák et al. 2020a, b). Considering that this class of pesticides is also causing persistent problems for wildlife in other countries (Sánchez et al. 2012, Walker et al. 2013, Nakayama et al. 2018), we are investigating the possibility of training the PCDDs to detect the most common anticoagulant rodenticides in the future.

The results of the first Spanish (Fajardo et al. 2012, de la Bodega Zugasti 2016) and Italian (LIFE ANTIDOTO 2014) poison detection dog units, and this later established Hungarian unit, has encouraged other organisations in Europe to start using this method in the fight against illegal poisoning of wildlife. However, the current high cost of training and maintenance only allows for a couple of these units to operate in Europe, mostly in the frame of EU-funded LIFE Nature projects (e.g. Vavylis et al. 2016). The PCDD unit of MME took an active part in the training of the first Bulgarian unit of the Bulgarian Society for the Protection Birds in 2016 (LIFE RE-Vultures project, unpublished data). In the Pannonian region the Hungarian Kiskunság National Park Directorate (one dog in one unit), the Czech Ornithological Society (two dogs in one unit) and the Slovak Police (two dogs in two units) trained PCDD units between 2017-2019 (PannonEagle LIFE project, unpublished data). The high efficiency of such dog units in poison detection and in other conservation applications makes the probable use of this method likely to be increasingly widespread to address a variety of conservation and biological problems in the future, not just in Hungary and neighbouring European countries, but also in other parts of the world.

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Supplementary online material

Fig. S1. The first two poison and carcass detection dogs (PCDDs) used in Hungary: a) "Falco" with a poisoned Eastern imperial eagle (*Aquila heliaca*; Fabiánsebestyén, Hungary, 17 January, 2019), b) "Carlo" with a beech marten carcass (*Martes foina*; Pusztavám, Hungary, January 2018).

Fig. S2. Typical photos from suspected wildlife crime scenes: a) the PCDDs with the findings of a field search after the police crime scene investigation and before the transportation of numbered evidence (poisoned specimens and baits) to the investigating laboratory (Újfehértó, Hungary, 09 March, 2020); b) some examples of poisoned baits found during searches.

Fig. S3. Geographical distribution of field searches executed by the PCDD unit in Hungary and neighbouring countries (n = 1,068).

Table S1. Type and quantity of searches and the number of detections by the PCDD unit in the different countries between August 2013 and August 2020.

Table S2. Types and species of poisoned specimens, poisoned baits and pesticide products found by the PCDD unit between August 2013 and August 2020 (n = 454). Protected species according to the national legislations are indicated with (P), and domestic species with (D). Search warrant findings are indicated with asterisks.

Table S3. Detected pesticides from poisoned specimens, poisoned baits and pesticide products found by the PCDD unit between August 2013 and August 2020.

(https://www.ivb.cz/wp-content/uploads/JVB-vol.-69-3-2020-DeakG.-ArvayM.-HorvathM.-Figs.-S1-S3-Tables-S1-S3.pdf)