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ORIGINAL ARTICLE

Understanding recreational targets and ecological consequences: increased northern pike stocking reflected in top avian predator diet

Tomas Virbickas[1] · Deivis Dementavičius[1] · Saulius Rumbutis[2] · Daiva Vaitkuvienė[1] · Mindaugas Dagys[1] · Rimgaudas Treinys[1]

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Abstract
Fish stocking is commonly used to enhance recreational fisheries; however, the side effects of stocking at the ecosystem scale have rarely been tested. Avian predators, because of their high position in food webs, can serve as indicators of environmental change, including prey-species abundance. The scope of this study was to understand whether recent changes in northern pike (*Esox lucius*) stocking on a national scale could cascade through food webs and significantly shape the diet of a predator—the white-tailed eagle (*Haliaeetus albicilla*). The stocking of pike in state-owned waters in Lithuania has increased two- to threefold since 2005. A significant increase in the proportion of pike in the breeding-season diet of the white-tailed eagle has also been observed. We explain the increase in pike in the predator's diet as being a causal consequence of pike stocking. We encourage consideration of the entire food web when launching/terminating recreational fish stocking programmes.

Keywords Fish stocking · Impact · Indicator · Prey · Raptor

Introduction

Fish stocking is commonly used to enhance recreational fisheries (Lorenzen 2014; Hunt et al. 2017). Among the native fish species, salmonids, northern pike (*Esox lucius*) and pike-perch (*Sander lucioperca*) are the most widely stocked in European inland waters (Food and Agriculture Organization 2005–2020). Stocking is extremely common, and has been employed uncritically for a long time (Welcomme and Bartley 1998). However, there is considerable evidence that stocking does not always produce the desired effect, due to competition with self-reproducing stock (Grønkjær et al. 2004; Sutela et al. 2004; Hühn et al. 2014), lack of suitable habitat (Skov and Berg 1999) or other factors (Guillerault et al. 2018). Moreover, the side effects of fish stocking in aquatic ecosystems have rarely been tested. Thus, better understanding how fish stocking influences trophic webs may contribute to the decision-making process through increasing the information pool on the ecological consequences of the socially targeted activity.

Different European countries rely on national rules and practices for fish stocking, and lack common strategies (Welcomme et al. 1983). In Lithuania, which has an abundance of inland waters, the stocking of fish in state-owned water bodies (ca. 75% of all inland waters) was not strictly regulated until 2002. The legislation only provided guidelines for stocking density, which were not required to be complied with (Ministry of the Environment of the Republic of Lithuania 1995, 1996). There were also no clearly defined criteria as to what species of fish should be stocked in one or another type of water body and at what intervals. In addition, illegal fishing has been common in Lithuania for decades. The first large scale survey of respondents on recreational fishery conducted in 2002 showed that at that time the fishing regulations were violated 4.8 million times a year, and only 0.1% of all violations were identified (Domarkas 2006). Since 2002, fish stocking became more closely controlled after the adoption of legislation on minimum fish stocking densities in 2002 (Official Gazette 2002), and the adoption of standard fish stocking programmes for different types of water bodies in

✉ Rimgaudas Treinys
rimga.t@gmail.com

[1] Nature Research Centre, Vilnius, Lithuania

[2] T. Ivanauskas Zoological Museum, Kaunas, Lithuania

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2005 (Official Gazette 2005a). These stocking programs included pike as the main fish species, because this species experiences the greatest impact from recreational fishing and pike stock was strongly depleted. Along with stocking, in 2004, the penalties for illegal fishing or caught individuals of illegal size were indexed (Official Gazette 2004). In 2009, the fines were increased 5 times, and in 2013, they were increased 5 times again (Official Gazette 2009, 2013). In addition, since 2005, it has been prohibited to use live fish as a bite in winter, and the minimum length of pike allowed for catching has been increased from 40 to 45 cm (Official Gazette 2005b). Finally, in 2014, the number of pike individuals that can be caught from the water body was reduced from 5 to 3 individuals (Register of Legal Acts 2014).

However, the effects of increased stocking together with stricter regulation of recreational fishing on pike abundance on a national scale remained unclear. Different lakes were stocked with pike juveniles of different ages and in different years, and fish assemblages are monitored only once every 6 years in most lakes; therefore, estimations of the impact of stocking, using only fish monitoring data, has been associated with certain degree of uncertainty. A system of accounting for fish catches by anglers in Lithuania has not yet been developed (Food and Agriculture Organization 2005–2020). Smartphone applications that could make it possible to conduct a more reliable survey of angler catches (Venturelli et al. 2017) have only just begun to be used in Lithuania, and are still not widespread.

Avian predators can substantially influence aquatic food webs, but are often neglected in the study of aquatic systems (Steinmetz et al. 2003). It has been empirically well documented that avian predators exhibit a numerical response to annual fluctuations and/or long-term shifts in principal prey species abundances (Reif et al. 2001; Tryjanowski and Kuzniak 2002; Newton 2003; Valkama et al. 2005; Rutz and Bijlsma 2006). Because of their high position in food webs, avian predators can serve as sentinels of environmental contamination (Helander et al. 2008; Grove et al. 2009), can indicate areas of high biodiversity or can be used to track population changes in prey species (reference in Donázar et al. 2016). Considering the above-mentioned, the dietary composition of the top avian predator can indicate the effect of management decisions acting at the aquatic ecosystem scale. The white-tailed eagle—the largest diurnal raptor in Europe (adult body mass ~ 3.1–6.9 kg)—recently experienced a recovery in its population, and has spread throughout coastal and inland ecosystems (Krüger et al. 2012). Despite the generalist dietary pattern of the white-tailed eagle (Whitfield et al. 2013), fish is a preferred prey over water birds (Nadjafzadeh et al. 2016b), while pike is its keystone species in some regions of Europe (e.g. Helander 1983; Sulkava et al. 1997; Ivanovski 2012).

In the present study, we asked whether recent changes in pike stocking on a national scale could be reflected in the diet of the white-tailed eagle. To answer this question, we gathered data on pike stocking activities and determined the temporal variation in pike as prey in successful white-tailed eagle nests, monitored between 2005 and 2018 in Lithuania. We predicted that pike would increase over time among the prey items in nests of the white-tailed eagle, and that the number of other fish species that were not subject to countrywide stocking would not follow the same trend. If the trend in pike stocking was reflected in the diet of the white-tailed eagle at its population scale, this would lead to a better understanding of how recreational fish management decisions may cascade through trophic webs.

Materials and methods

Pike stocking data

Data on the number of juvenile pike stocked in inland waters in 2000–2018 were obtained from the Fisheries Service of the Ministry of Agriculture and from the Ministry of the Environment. Both institutions are responsible for the management of fish resources and the stocking of native fish species in state-owned water bodies in Lithuania. Since the age of the stocked juvenile pike varied between water bodies and years, the number of all stocked pike was converted to the equivalent of 0+-year-old pike, multiplying by a factor of 0.017 for yolk-sac pike fry and by a factor of 0.33 for pike fingerlings at the age of 6 weeks (Szczerbowski et al. 1993). A theoretical yield of 4+-year-old pike was calculated using an annual mortality rate of 0.75 (Kipling and Frost 1970). White-tailed eagles catch prey in a rather narrow weight range, mostly between 0.5 and 1 kg (Sulkava et al. 1997). In Lithuanian freshwaters, pike assume that size, on average, at 4 years of age (Virbickas 2000).

White-tailed eagle prey data

Prey remains were collected from the nests of white-tailed eagle pairs nesting in different areas of Lithuania (Fig. 1) where the breeding territories and nests had been searched and monitored over the last two decades (a detailed description of the field procedures has been provided in Treinys et al. 2016 and Kamarauskaitė et al. 2019).

Dietary samples were collected once per season, during the ringing of nestlings in May–June, between 2005 and 2018. Altogether, we observed 277 successful breeding attempts of 60 white-tailed eagle pairs, which constitute ca. 33% of the Lithuanian population. Prey and their remains were identified to the lowest identifiable taxonomic level. Fresh, whole or otherwise easily identified prey items were identified in the field. The remaining items, such as body parts, bones, feathers, fur and skulls, were collected and identified later

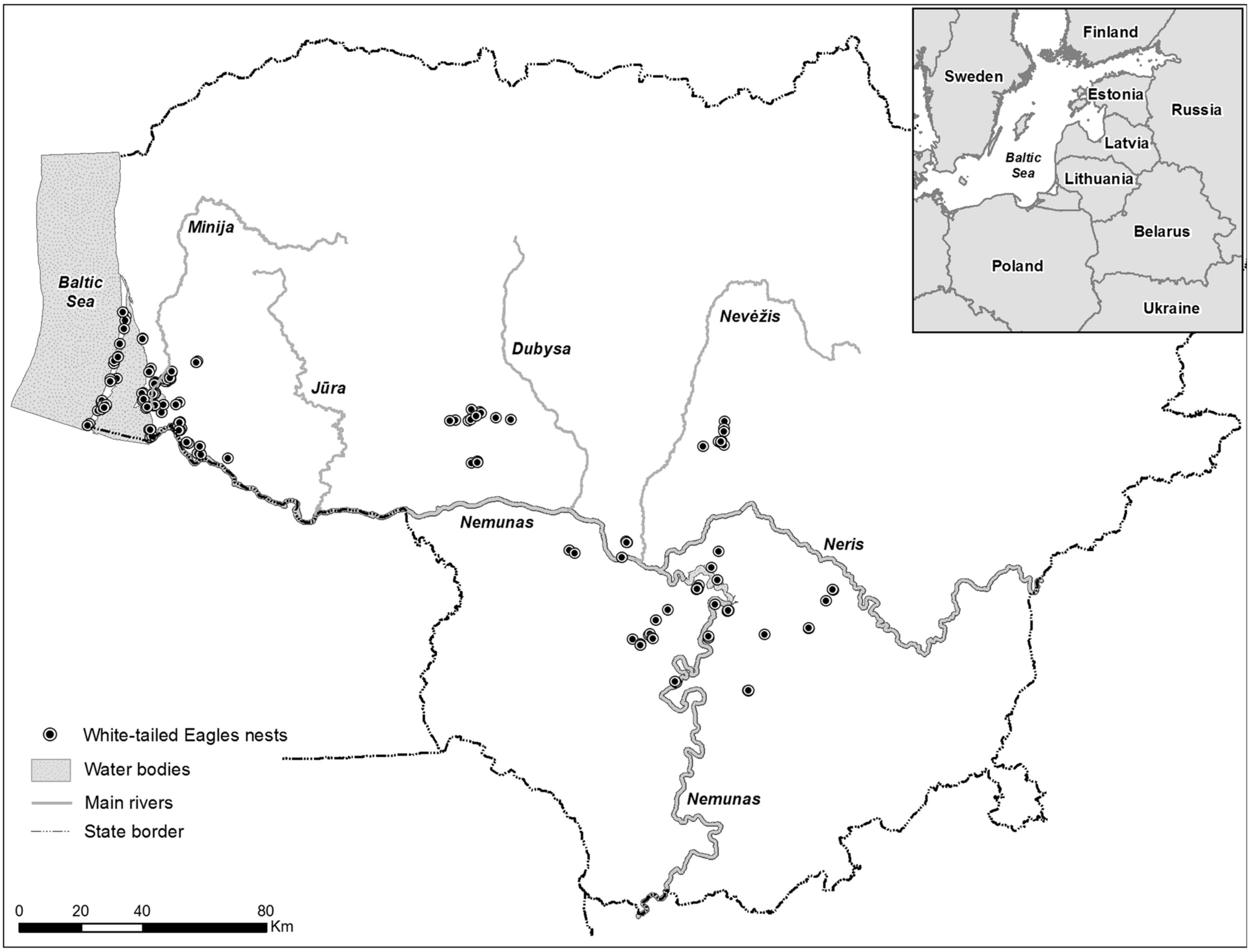

Fig. 1 Location of sampled white-tailed eagle nests

using reference animal collections in the T. Ivanauskas Zoological Museum (Kaunas, Lithuania). The 'minimum approach' was applied when counting the number of prey items from the remains (i.e. if two different parts of the same species were found, they were recorded as belonging to only one individual). Pike weight for 347 specimens was estimated by measuring specimens with the rule, either by comparing parts of their skulls with those in a reference collection of pike specimens of known size in the Kaunas T. Ivanauskas Zoological Museum, and was approximated to the nearest 0.1 kg. Overall, estimated size of pikes is rather coarse, and two approaches applied for estimation of weight might introduce some variations within the sample, but these methods were applied interchangeably over study period depending on specimen 'condition' without temporal bias.

Data analysis

Using generalised linear models (GLMs, family Gaussian, link identity), we tested the temporal changes (i.e. year as the explanatory variable) in the following response variables: (1) expected annual number of pike at age 4+ years, (2) number of sampled nests per year, (3) annual proportion (%) of nests with pike remains detected among all sampled nests and (4) annual proportion (%) of pike among all prey items sampled.

Generalised linear mixed models (GLMMs) were used to test temporal changes in the (5) number of pike individuals per nest (included only nests where at least one pike specimen found, n = 137) (family Poisson, link log; 'territory identity' was included as random factor), (6) number of other fish individuals per sampled nest (included only nests where at least one other fish specimen found, n = 201) (family Poisson, link log; 'territory identity' was included as random factor) and (7) weight of the pikes found in the nests (family Gaussian, link identity; 'territory identity × year' interaction was included as random factor because several pike specimens found in the same nest in particular year are clustered events). The packages *lme4* (Bates et al.

2015), *sjmisc* (Lüdecke 2018), *sjPlot* (Lüdecke 2019) and *ggplot2* (Wickham 2016) were used in the statistical environment R version 3.6.0 (R Core Team 2019).

Results

Data on pike of different ages released into state-owned water bodies in 2000–2017 are presented in Table 1. The annual number of stocked pike, converted to the equivalent of 0+-year-old individuals, increased from 365 000 in 2000 to > 1,000.000 in recent years. As a consequence of pike stocking, the estimated availability of stocked pike that reached 4+ years old must have increased significantly since 2005 (GLM: 16900 ±5450 SE, $p < 0.01$; Fig. 2a).

The national population of white-tailed eagle nearly doubled between 2005 and 2018, from ca. 90 to 160 pairs, and significant positive trend was also reflected in the areas studied by us (GLM: 1.03 ± 0.18 SE, $p < 0.001$) where the number of successful nests increased from a mean of 13 nests during the first 3 years to a mean of 25 nests over the last 3 years of the studied period (Fig. 2b). The percentage of nests in which pike occurred as prey among the sampled items also increased significantly (GLM: 2.85 ± 0.81 SE, $p < 0.01$); for example, during the first 3 years of the study, pike remains occurred in no more than 33% of the checked nests, whereas during the last 3 years, the annual proportion of nests containing preyed pike was between 56 and 71% (Fig. 2c). Overall, pike composed 19% of the prey items identified ($n = 2163$), but the annual proportion increased significantly during 14-year period studied (GLM: 1.82 ± 0.42 SE, $p < 0.01$). The mean annual proportion of pike among the sampled prey items was 6% in the first 3, and 23% in the last 3 years (Fig. 2d).

The number of pike items in white-tailed eagles nests also increased significantly over the years (GLMM: 0.06 ± 0.02 SE, $p < 0.001$; Fig. 3), but the decrease in number of prey items of other fish species found (GLMM: − 0.03 ± 0.01 SE, $p < 0.01$). The estimated weight of the pike found among the prey items in the successful nests of white-tailed eagles averaged 0.87 kg ± 0.52 SD, interquartile range 0.5–1.0 kg ($n = 347$). The changes in weight of the preyed pike during study period was not supported by the data (GLMM: − 0.007 ± 0.01 SE, $p > 0.5$).

Discussion

In the present study, the dynamics of pike stocking in state-owned water bodies was compared with the occurrence of pike in the nests of a top avian predator for which pike is a keystone prey species during the breeding period. The stocking of pike in the inland waters of Lithuania has increased two- to threefold over quantities in the initial years of the programme, when stocking was weakly implemented. Stocked pike individuals also begin to reproduce as they reach maturity, at 2–4 years old (Raat 1988). Therefore, the stocking

Table 1 Number of pike (in thousands) stocked in state water bodies in 2000–2017

Year	Yolk-sac fry	Fingerlings	0+ age	Total (converted to 0+ age equivalent)	Expected number of pike at the age of 4+ years
2000	20 528		22.4	365.2	116.0
2001	22 157		38.6	408.6	129.8
2002	29 757		91.9	588.8	187.0
2003	28 000		16.8	484.4	153.9
2004	30 695	550	384.6	1078.7	342.7
2005	28 460	200	216.2	757.5	240.6
2006	13 034	1925	269.5	1122.4	356.6
2007	28 200	400	400.0	1002.9	318.6
2008	25 300	400	240.0	794.5	252.4
2009	26 060	280	78.1	605.7	192.4
2010	31 960		79.1	612.9	194.7
2011		3050	80.8	1087.3	345.4
2012		4100	64.2	1417.2	450.2
2013		4150	88.7	1458.2	463.2
2014		3091	60.0	1079.9	343.1
2015		3100	158.8	1181.8	375.4
2016		3322	26.0	1122.3	356.5
2017		3069	25.7	1038.4	329.9

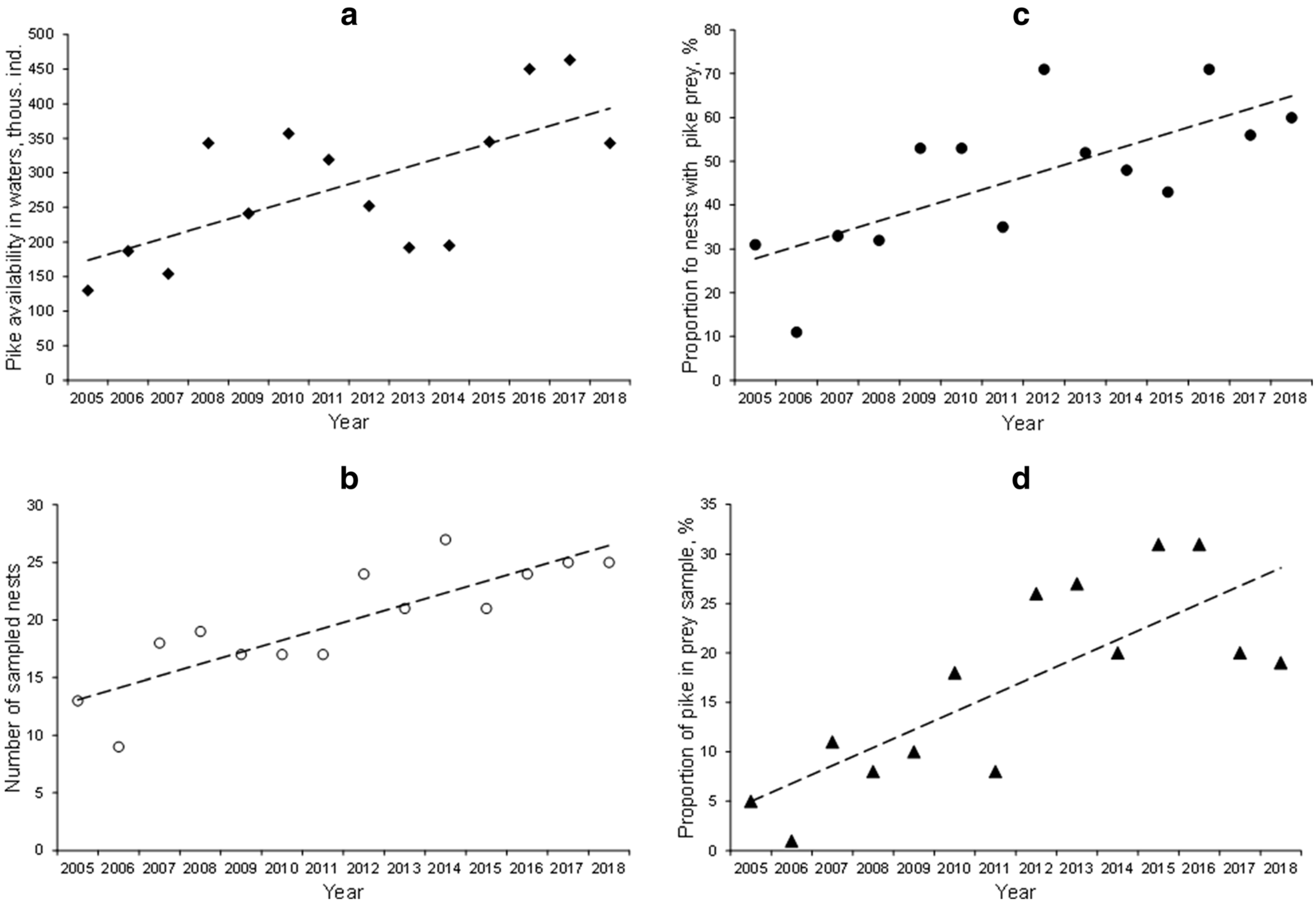

Fig. 2 Dynamics of the annual expected number of stocked pike at the age of 4+ years (**a**), annual number of sampled nests (**b**), annual proportion of nests with pike among the prey items (**c**), and annual proportion of pike in the white-tailed eagle diet (**d**) between 2005 and 2018

might have contributed to an increase in the resources of pike not only directly, but also indirectly to a certain extent, by

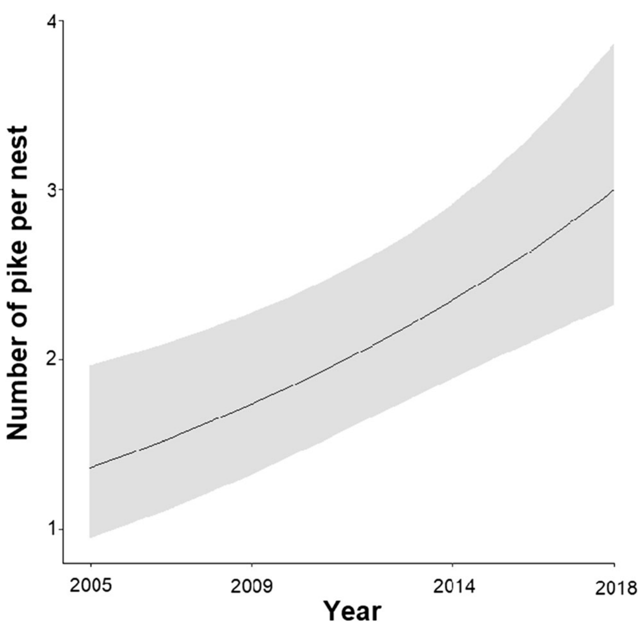

Fig. 3 Predicted number of pike items in the white-tailed eagle nests between 2005 and 2018, as estimated by GLMM

facilitating natural reproduction. All this together with the stricter regulation of recreational fishery should have led to a marked increase in pike resources in the country. The number of breeding pairs of the national population of white-tailed eagle in the studied areas also nearly doubled during the same period. Pike items were recorded in a large share of the sampled nests in recent years, and the number of pike items per nest increased throughout the study period, resulting in a several-fold increase in the proportion of pike in the breeding season diet of this avian predator. On the other hand, number of prey items belonging to other fish species decrease in white-tailed eagle nests during the breeding season. In summary, despite the comparative nature of our study, we propose that the programme of pike stocking in inland waters has affected the aquatic ecosystems by adding a considerable biomass of this fish species, and the top avian predator has responded by increasing its utilisation of its preferred prey species.

The efficiency of pike stocking activity has been suggested as questionable (Guillerault et al. 2018), but our results indicate an overall increase in pike stocks in Lithuanian water bodies likely as a consequence of stocking together with the stricter regulation of recreational fishery. Our suggestion is supported not only by the pike increase in eagle diet, but also by the data of two recent studies. First study was conducted by the standardised fish sampling method (see Virbickas and Stakėnas 2016) under the initiative of the Ministry of Environment of Lithuania on pike stocks in 115 lakes stocked between 1 and 8 years before the study (Virbickas 2016, 2018). The study revealed that pike individuals at an age corresponding to the stocked cohort accounted for 30% to 100% of the total pike catch in 28 out of the 46 lakes where sampling was conducted 2–4 years after the pike stocking. In the remaining 18 lakes, pike specimens were either of a different age, or were completely absent from the catches (3 lakes). Nevertheless, the average catch per unit effort of pike with a standard multi-mesh bottom gill net in these 46 lakes (0.35 ind. ± 0.25 SD) was significantly higher than in the remaining 69 lakes (0.18 ind. ± 0.18 SD), where pike was not stocked or it was stocked more than 4 years before the study (Mann-Whitney U test; $p < 0.01$). The second survey of recreational fishing respondents, conducted in February–March of 2020, found that among fish species, pike catches were the highest (26%) followed by perch (24%), bream (21%) and roach (11%) (Inland Fisheries Study 2020). In summary, pike stocks in Lithuanian water bodies were severely depleted prior to the stocking program; therefore, we suggest that the stocking effect may have been greater than would have been expected in water bodies containing larger natural stocks of pike (Guillerault et al. 2018).

Not only the increase in pike stocking, but also other factors, related to pike ecology and catch restrictions, have been favourable for the white-tailed eagle. An increase in the minimum permitted length for pike fishing, from 40 to 45 cm, which took place in 2006 (Official Gazette 2005b), may have had an additional effect, since this provided an additional share of pike resources for use by the white-tailed eagle, without competition from fishermen. In Lithuanian waters, it is forbidden to catch pike from February 1 to April 20, protecting its spawning, which usually occurs from mid-March to mid-April (Virbickas 2000). A pike can arrive at the spawning grounds 3–4 weeks before the spawning begins (Raat 1988). In the case of a cold spring, the spawning period is extended, and so the ban on pike fishing is subsequently extended until the beginning of May. Throughout this period, which can last up to 2 months, the pike stay and spawn in shallow water, at a depth of 0.25–1 m (Raat 1988) and are not harvested by fishermen. A depth of up to 1 m is accessible to the white-tailed eagle for catching prey (Sulkava et al. 1997). After spawning, the pike feed intensively, also in the shallows or near the water surface, until the water temperature rises to ~ 18–20 °C (Diana et al. 1977; Žiliukienė and Žiliukas 2002). During this period, the pike remains a relatively easy prey for the white-tailed eagle, although the latter would, by this time, already be competing with fishermen for the > 45-cm pike individuals. When the water temperature exceeds 20–22 °C, the pike move to deeper habitats. In Lithuania, this temperature is usually reached in the second half of June–early July; that is, at the time of white-tailed eagle fledging.

The proportion of pike in the breeding-season diet of the white-tailed eagle clearly differs across its breeding range, the highest having been observed in Northern and Eastern Europe (Sweden: 26–39%, Helander 1983; Finland: 32.5%, Sulkava et al. 1997; Belarus: 27.5%, Ivanovski 2012) and < 10% having been observed in other populations across its range (Germany: 7%, Struwe-Juhl 2003; Danube delta: 6%, Sándor et al. 2015; East Siberia: 6%, Mlíkovský 2009). The Lithuanian white-tailed eagle diet, in terms of pike importance (19%), falls in between the above-mentioned distinct regions, especially considering that, during the studied period, the proportion of pike grew from ca. 6 to ca. 23% of the total prey found. We do not see any potential for sampling bias in the observed results: (1) the fieldwork was performed by the same persons; (2) the intensity and timing of the sampling of the prey remains was constant over the study period; and (3) the detectability of pike remains in the nests should also not have changed because the white-tailed eagle usually does not crush the lower jaws (Sulkava et al. 1997) or even the skulls of the pike (the authors, pers. obs.).

We can explain the observed increase in pike prey over the study period as a causal consequence of pike abundance increases in Lithuanian water bodies, and provide several arguments to support this.

(1) Optimal foraging theory predicts that animals specialise in their most preferred prey (Pyke et al. 1977). White-tailed eagle feeding behaviour is consistent with the optimal foraging theory, as reported by Nadjafzadeh et al. (2015). Pike has also been found to be the preferred prey of the white-tailed eagle because it is over-selected compared to its availability in waterbodies (Nadjafzadeh et al. 2016b). In Lithuania, white-tailed eagle nestlings grow between mid-April and June (Drobelis 2004); that is, the period covering pike spawning and active feeding after spawning, when it is frequently available at the water surface (see above). Furthermore, fish prey in the white-tailed eagle diet peak during the breeding season compared to the rest of the year (Helander 1983; Struwe-Juhl 2003; Nadjafzadeh et al. 2015). Hence, a low occurrence of pike in the diet during the first years of the study can most likely be explained by the limited availability of pike in the water bodies in the breeding territories rather than the under-selection of pike by the white-tailed eagle.
(2) Predators are known to show numerical and functional responses that correspond to the varying main prey densities (Korpimäki and Norrdahl 1991; Reif et al. 2001; Valkama et al. 2005). A numerical response can be described as a change in predator numbers (or breeding output per pair) in relation to the density of the main

prey. We observed that the proportion of white-tailed eagle pairs with the occurrence of pike items in their nests increased together with the total number of pairs in our study areas. This means that more predator pairs in the population were able to utilise pike over time. Functional responses in predators can be described as changes in the prey capture rate in response to the prey's density. We found that the number of pike prey items increased per nest over time, suggesting that the increase in pike density resulted in more captures by white-tailed eagles in their breeding territories.

(3) Optimal foraging theory predicts that food types are ranked first by their nutritional value to handling time ratios (Pyke et al. 1977). Nadjafzadeh et al. (2016b) pointed out that prey of intermediate to larger sizes can be more profitable compared to the largest prey a predator can handle, reporting that white-tailed eagle over-selected medium-sized pike (i.e. up to 50 cm in length), whereas larger pike were utilised in proportion to their availability in the water bodies in the breeding territories. The pike weight estimated in our study (mean 0.87 kg) was similar to the weight of pike (mean 0.75 kg) found in the food remains of white-tailed eagle nests on the Baltic Sea coast in Sweden (Helander 1983). No trend in predated pike weight was observed in our data; therefore, we suggest that increased predation on pike of optimal size class by white-tailed eagle further indicates saturation of pike in the aquatic ecosystems of Lithuania, but not a switch of the eagles to another size class of the pike.

Conclusions

(1) The survival of stocked fish in natural conditions, and their impact on the overall abundance of target species, depend on many factors (Cowx 1994). Equally important is how resources are exploited (Jansen et al. 2013). Various factors can significantly affect stocking efficiency, which can make the direct assessment of changes in fish stocks on a regional scale very difficult. Raptors, on the other hand, can act as sentinels of local and large-scale environmental changes, including the dynamics of their prey populations and environmental contamination (Helander et al. 2008; Grove et al. 2009; Donázar et al. 2016). We propose that the monitoring of the diets of top avian predators, especially if complemented by video recording analysis (Selås et al. 2007), could be used to track the population dynamics of their preferred prey species at the local and larger scales.

(2) We encourage a broader ecological assessment—that is, consideration of the entire food web—of the potential impact of the initiation or termination of recreational stocking programmes. Large-scale programmes should be assessed the most carefully because they act at the ecosystem scale and are highly dependent on funding and/or political decisions, thus could be terminated unpredictably, despite planned time schedules. The abundance of the preferred prey of an avian predator is linked to its vital demographic traits (Resano-Mayor et al. 2016). Thus, a decrease in the preferred prey could result in population limitations (references in Newton 2003; Rutz and Bijlsma 2006) that could include predator species that may be of concern in terms of conservation. On the other hand, when the preferred prey of a generalist predator decreases in abundance, the predator may switch to alternative prey species (alternative prey hypothesis: Reif et al. 2001) that may include species of conservation concern or other raptors (Rutz and Bijlsma 2006; Lourenço et al. 2011; Hoy et al. 2017). It is well known that top predators can affect mesopredators through lethal and/or non-lethal effects, which can alter the trophic interactions in an ecosystem through the 'mesopredator suppression' mechanism (Chakarov and Krüger 2010). The white-tailed eagle is known to adjust its diet between seasons, years and along environmental gradients (at the local and regional scale) (Helander 1983; Struwe-Juhl 2003; Ekblad et al. 2016; Nadjafzadeh et al. 2016a, 2016b), and can prey upon birds of conservation concern (Dementavičius et al. 2020), as well as other raptors (Kamarauskaitė et al. 2019). Therefore, decisions on the initiation/termination of pike stocking programmes on a regional scale that involve a considerable amount of fish may indeed cascade through the trophic interactions in aquatic and terrestrial habitats, which could raise conservation concerns particularly in the Northern and Eastern European countries that support strong populations of white-tailed eagle.

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Authors' contributions Not applicable

Availability of data and material The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Compliance with ethical standards

Conflict of interest/Competing interests The authors declare that they have no conflict of interest.

Ethics approval All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

Consent to participate Not applicable

Consent for publication Not applicable

Code availability Not applicable

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