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CHAPTER 5

Reduction of adverse effects of tracking devices on waterfowl requires better measuring and reporting

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ABSTRACT

Since the first studies in the mid-20th century, lightweight electronic tracking devices have been increasingly used to study waterfowl movements. With half a century of experience and growing sample sizes, it has become clear that the attachment of a tracking device can affect a bird's behaviour and fitness. This becomes problematic when it introduces uncertainty about whether the recorded data represent natural behaviour. Waterfowl may be particularly prone to tag effects, since many species are migratory and tracking devices can disrupt their waterproof plumage. The primary aim of this paper is to identify how tracking devices may affect waterfowl survival, migration and reproduction, and how better measuring and reporting of such effects can improve our understanding of the risks, providing a first step towards reducing their impact in future studies. We reviewed literature on electronic tracking of waterfowl to create an overview of currently recognized effects of harness-attached backpacks, implants, subcutaneous attachments and neck collars. Additionally, we analysed developments in the use of attachment methods, the weight of tracking devices relative to bird body mass, and the reporting rate of effects of tracking devices in 202 original tracking studies. We found that although the number of waterfowl tracking studies described in peer-reviewed literature has steeply increased over the past decades, reporting rates of potential effects have decreased from 65.0% to 26.5%. Meanwhile, the mean weight of the tracking devices relative to the bird's body mass remained stable around 2.0%. Major negative effects were reported in 17% of all studies and were found for all attachment methods. Overall, large differences exist in the occurrence and type of negative effects between species and studies, even if the same tracking methods were used. Inconsistent reporting of effects, lack of control groups to measure effects and incomplete descriptions of the methodology hamper the identification of factors contributing to these effects. To accomplish a reduction of adverse effects of tracking, it is necessary to improve the measuring and reporting of effects. We propose a framework for standardized reporting of methods in primary tracking studies and standardized protocols to measure effects of tracking devices on waterfowl.

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Introduction

The development of lightweight electronic tracking devices, which can transmit or log global positions and are small enough to deploy on free-ranging wild birds, has unchained a revolution in ornithology (Bridge et al. 2011). Such devices enable tracking of birds during their entire annual cycle, and assessing fine-scale movement behaviour and individual behavioural strategies, which is difficult or impossible using conventional marking methods (metal rings or colour bands), especially in long-distance migrants. The ability to remotely track bird movements with high resolution and accuracy, for example using current GPS-transmitters (up to 5m accuracy with a GPS-fix every 3 seconds), has greatly improved our understanding of their behaviour and ecology, with important implications for their conservation (Kays et al. 2015). Due to their large body size, waterfowl (swans, geese and ducks) were already tracked regularly by radiotelemetry since the 1960s (e.g. Raveling 1969). When satellite transmitters were introduced in the 1980s, waterfowl were among the first birds to which attachment of the relatively large first models was considered acceptable (e.g., Trumpeter Swan *Cygnus buccinator* and Tundra Swan *C. columbianus*; Strikwerda et al. 1986). As tracking devices became smaller, lighter and cheaper over the years (Bridge et al. 2011), their use on birds has become a well-established tool in ornithology and an increasing number of species are being tracked in their natural habitat.

However, with an increasing availability of tracking devices and the corresponding increase of individual birds on which they are being deployed, the need to understand and reduce their potential detrimental effects on birds is ever pressing. A growing number of publications show that tracking may come with a cost for the animal, which becomes especially problematic when it affects the measured behaviour (reviewed in Barron et al. 2010; Calvo & Furness 1992; Murray & Fuller 2000; White et al. 2013). Among the negative effects identified in these reviews are increased mortality, disturbed (migratory) behaviour and reduced reproductive success, eventually resulting in lower fitness. Study species, transmitter type and attachment method are the most obvious factors that may determine the effect on a bird and thus the success or failure of a tracking study. Taking these factors into account when designing a telemetry study is not only important for animal welfare, but will also ensure that the researcher can be confident that the observed behaviour (e.g., migration strategy) is not an artefact of the tracking method (Wilson & McMahon 2006). Thorough understanding of such factors, especially prior to studying an unfamiliar species or using unfamiliar materials or techniques, requires open communication among researchers and the exchange of positive as well as negative experiences from the field.

Important contributions to communication about effects of telemetry on birds have already appeared in scientific literature. A comprehensive meta-analysis of transmitter effects on a wide range of bird species by Barron et al. (2010) has shown that tracking devices often (but some more than others, see White et al. 2013) affect the birds carrying them. Although the study did not find a direct effect on flight ability, some degree of negative effects were found for all other aspects of the birds' ecology and behaviour covered in this study. Energy expenditure and the probability to initiate nesting were most strongly affected, with obvious long-term fitness consequences. A meta-analysis of tagging effects on seabirds (Vandenabeele et al. 2011) found that despite a growing number of studies making use of tracking devices, still relatively few studies explicitly consider the possible adverse effects on their study species.

In this study, we focus on waterfowl (Anatidae), a group of birds that, despite their large body size, may be particularly prone to negative effects. Many waterfowl populations are migratory (del Hoyo et al. 2016) and may be energetically constrained by carrying a tag (Pennycuick et al. 2012). Also, due to their aquatic habitat, the breaching of their waterproof plumage by device attachment may affect their thermoregulation (Bakken et al. 1996; Latty et al. 2016; Paquette et al. 1997). Thanks to the long history of waterfowl tracking, much experience has been acquired by researchers in the field. Accordingly, papers discussing effects of loggers on several waterfowl species appear regularly in literature, but considering the vast number of species tracked in the past decades, much more information on the extent of these effects must be available. Disclosing this information is essential to improve tracking methods and reduce the associated negative effects. The primary aim of this paper is to identify which problems are associated with different tracking methods and study species, and to set out directions towards the reduction of adverse effects in future studies, for which we deem improved measuring and reporting of these effects an important first step.

To this end, we reviewed the effects of tracking devices and attachment methods described in literature and evaluated the occurrence and the reporting rate of effects in 202 primary tracking studies. Based on our findings, we propose a standardized format for reporting details of tracking methods used in waterfowl studies and give suggestions on how studies can be set up in order to improve detection of potential adverse effects of tracking devices on the study species. We hope that this will facilitate identification of best practice methods for each combination of tracking method and waterfowl species. It is important to note that many of the field studies covered in this paper are based on pioneering work and it is explicitly not our intention to judge the practices of any individual researcher or research group. Rather, we hope to show here that these studies are now invaluable for evaluating how we can prevent problems in the future, which will ultimately lead to better science.

Methods

To evaluate the occurrence and reporting rates of potential effects, we performed a literature search in Web of Science and Google Scholar in December 2015 using the following search terms: (goose OR swan OR duck) AND (tracking OR GPS OR telemetry). We then included every study which was performed in the field (no captivity studies), and which used any attached electronic tracking device on waterfowl (thus including the full range of VHF-transmitters, PTT satellite transmitters, GPS-loggers, GPS-GSM transmitters and geolocators), attached using any method (thus including harness attachments, implants, neck collars, subcutaneous attachments, and other methods). We complemented this list by reviewing cited and citing papers, finally resulting in a set of 202 relevant studies (see Table S5.1 in the Supporting Information for the complete list). Note that this list of waterfowl tracking studies is not fully comprehensive, but provides a representative sample for our evaluations. From this set of studies, we extracted basic details on tracking methods, study species, whether effects of tracking devices were reported and which effects were reported, when possible subdivided in effects on survival, migration and reproduction (Table S5.2). We considered a study to report effects if it compared the performance of birds equipped with tracking devices with a control group or with data extracted from earlier studies or other literature. For studies not reporting the body mass of the birds, we extracted the mean body mass for the relevant species and sex from the Handbook of Birds of the World (del Hoyo et al. 2016). If it was unclear which sex was tracked, we used the average weight of males and females taken together. By dividing the weight of the tracking device by the bird's body mass, we calculated the relative weight of the tracking device. For this calculation we excluded studies that failed to report the weight of the tracking device or did not specify device weights used for different study species. For classification of the attachment methods, we followed the definition of Roshier & Asmus (2009): 1) harness backpack, 2) abdominally implanted, 3) anchored in skin, and 4) neck collar. Their fifth category was "tags attached to feathers", but this method was used so rarely that we combined it into an "other methods" category, including also tags glued to other parts of the body, or to plastic leg rings. For the category of harness backpacks, we found only studies using wing loop attachments, none of the studies in our analysis used leg loop attachments.

Waterfowl tracking - a brief history

Our literature review revealed that the use of telemetry to remotely track waterfowl movements has increased rapidly over the past three decades (Figure 5.1). So far, tracking devices have been deployed on waterfowl on all continents where waterfowl occur and included at least 54 species. Most tracking studies have been carried out in North America, making up 63% of the papers in this review. Europe and Asia lag far behind, accounting for 18% and 12% of the tracking studies, respectively. Less than 5% of all tracking studies were carried out in Africa and Australia, and our literature search revealed only one study from South America. The first tracking studies were carried out in the 1960s (first studies in our review were carried out in the 1970s) and exclusively used radio-transmitters. The first published study using platform transmitter terminals (PTTs, also known as satellite transmitters) appeared in 1986, and since then PTTs have become most used device in telemetry studies (Figure 5.1a). However, since its first appearance in 2005, tracking devices using GPS have become increasingly popular in waterfowl telemetry and studies using this method already made up 42% of the publications in 2015. It would be expected that studies using GPS devices will soon outnumber those using PTTs. Clearly, this field of research is still under rapid development.

Although tracking devices have changed over the years, the relative use of different attachment methods has remained largely unchanged (Figure 5.1b). Backpack harnesses, the first method used to attach tracking devices, are still the most common method, followed by implantation. Neck collars were used more often in the early 2000s, but have been used irregularly in the past 10 years. Apart from differences between attachment methods in adverse effects for waterfowl, the choice of attachment method should also depend on the research question of the researcher (Kölzsch et al. 2016b). Harness-attached backpacks have the benefit of bringing the tracking device close the centre of gravity of the bird (Kölzsch et al. 2016b), while its placement on the back creates a large surface for charging of solar panels. Transmitter implantation in the abdominal cavity is sometimes preferred over the use of backpacks, especially in diving species, since this overcomes the problem of interruption of the waterproof plumage, as well as the problem of drag created by external devices during flying or diving. The main drawbacks of this method are that it does not allow the use of a solar panel to charge the batteries and that the procedure requires surgery by a specialized veterinarian. Mortality during or shortly after surgery can occur (e.g. Rosenberg et al. 2014), and some studies using internal antennas also report a limited signal range of the transmitter as a major disadvantage (Olsen et al. 1992). Tracking devices can also be attached partly or completely subcutaneous. After making a small incision in the skin, either anchors attached to the tracking device (on one or two ends, e.g., Lewis et al. 2008) or the complete tracking device can be placed under the skin (e.g. Korschgen et al. 1996a), after which the incision can be closed by suture and/or glue. Depending on the scale and duration of the operation, birds can be briefly anesthetized (e.g. Brook & Clark 2002). An important drawback of this attachment method is the high loss of subcutaneously attached transmitters, as was found in studies on Mallard *Anas platyrhynchos* (31 out of 49 transmitters lost, Rotella et al. 1993), Northern Pintail *Anas acuta* (37 out of 82 lost, Fleskes et al. 2003) and Northern Shoveler *Anas clypeata* (20 out of 42 lost, Zimmer 1997). Neck collars with inscriptions are a common method to mark waterfowl, especially longer-necked species, for easy recognition in the field (e.g. Murray and Fuller 2000; Clausen and Madsen 2014), but they can also be used as a basis for the attachment of tracking devices. As neck collars are exterior, they can be used for devices working on solar power.

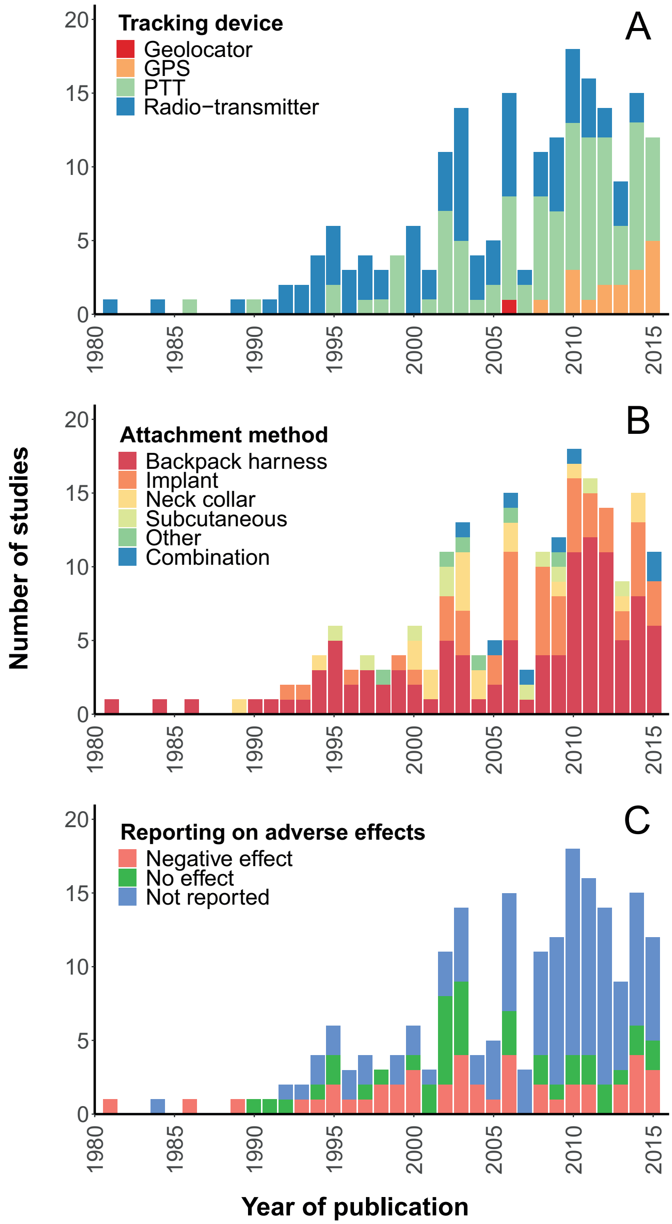

Figure 5.1: Use of tracking devices, attachment methods and reporting rates over years of publication. Number of studies per year of publication, split per tracking device type (a), attachment method (b) and whether the study reported on potential adverse effects (c).

Since the start of telemetry in birds, the mass of the tracking device relative to the bird's body mass has received much attention to make sure that the bird would not carry too much additional load. As a rule of thumb, devices weighing up to 5% of the body mass were considered acceptable and this was later reduced to a preferred 3% as tracking devices became smaller (Kenward 2001). Already in the first telemetry studies in waterfowl, the relative mass of tracking devices was kept around 3% of the bird's body mass. This was mainly due to the large species selected for these studies. Despite the decreasing weight of tracking devices over time (especially PTTs and GPS transmitters, Figure 5.2a), the weight relative to the bird's body mass has not decreased much on average and remained stable around 2%, with occasional extremes within studies down to 0.1% and up to 6.5% of the bird's body mass (Figure 5.2b).

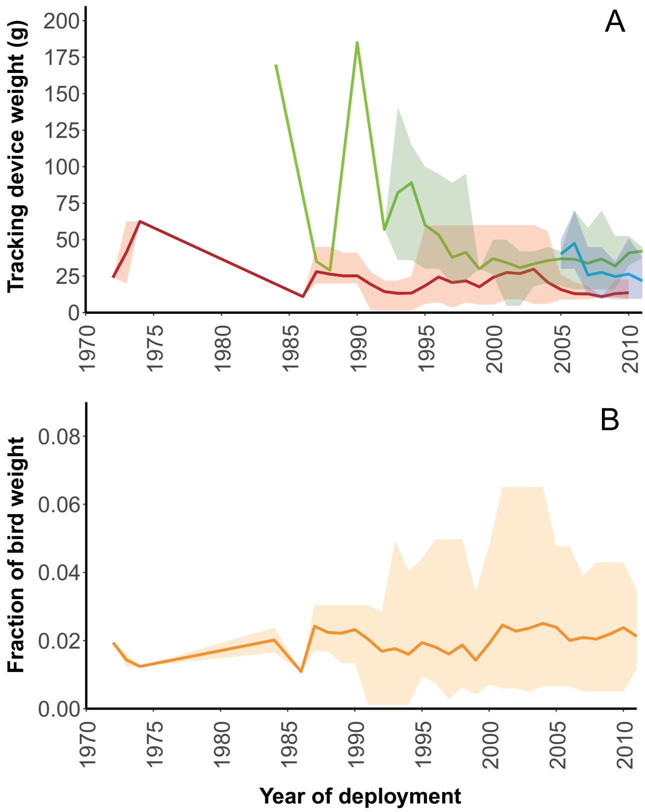

Figure 5.2: Changes in weight of tracking devices over study years. (a) Average weight in grams of tracking devices used in study years with coloured areas delineating the region between maximum and minimum weight, for radio-transmitters (red), PTTs (green) and GPS devices (blue). (b) Average weight of tracking devices as a fraction of the weight of the bird on which it was deployed, with the coloured area delineating the region between minimum and maximum fraction of weight.

Part of the explanation for this is that smaller devices are used to track smaller waterfowl species. Radio transmitters have long been light enough to track small duck species, but only since a few years these species could be tracked using PTT or GPS devices, which provide much more data. The first waterfowl species lighter than 500 g to be tracked using modern tracking devices was the Eurasian Teal *Anas crecca* (mean weight 325 g), tracked with 9.5 g GPS-PTTs in 2007 (Palm et al. 2015). Another important explanation is that with the development of telemetry techniques, researchers opted for novel devices with more possibilities, rather than reducing device weight.

Effects of tracking devices on waterfowl

An important first step towards avoiding or reducing effects of deploying tracking devices on waterfowl is to know what can go wrong. We found that 17% of all original tracking studies (40% of studies reporting potential effects) reported major, long-lasting negative effects of their tracking method. Here, we review the effects of different transmitter attachment techniques on waterfowl, including effects on survival, behaviour, migration and reproduction.

Harness-attached backpack

Harness attachment methods can have strong negative effects on survival. In one of the first studies using a harness as attachment method, all swans equipped with PTTs died before or during migration, which was attributed mostly to the weight of the 170 g devices (Strikwerda et al. 1986). Over the years it has become clear that apart from the burden of carrying a heavy device, harness backpacks themselves are probably the main cause of deleterious effects on the birds carrying them. The main problematic features of harness backpacks are that they are relatively large external structures causing abrasion and drag, disrupt waterproof plumage and that the harness may be too loose or too tight, partly depending on the bird's body stores, which can vary greatly over the year especially in migrants (Perry 1981; Garrettson et al. 2000; Pennycuick et al. 2012; Kesler et al. 2014). Effects on survival are most often detected by low return rates of tagged birds to breeding or staging sites compared to ring-marked individuals. The lowest return rate was reported in a study on female Barrow's Goldeneyes *Bucephala islandica*, with none of 16 tagged birds being recaptured in nest boxes during successive breeding seasons, relative to a background return rate of 66% (Robert et al. 2006). Almost as poor was the 4% return rate of 62 Brent Geese *Branta bernicla* fitted with backpack transmitters to their Alaskan breeding site, compared to 57-83% return rates of colour-ringed individuals (Ward and Flint 1995). In a study in Saskatchewan, Canada, Mallards with harness transmitters had a return rate of 22.6% to their breeding grounds compared to 55% in individuals with an implanted transmitter (Dzus & Clark 1996). Given the high site fidelity of these species, mortality is the most likely cause of these low return rates, although emigration cannot be fully ruled out. In contrast, other studies did not find any effects of harness attachments on survival. Survival rates over the course of the breeding season did not differ between Blue-winged Teals *Anas discors* with a harness backpack (61% survival over 90-day period) and individuals with an implanted transmitter (73% survival over 90-day period), and although both groups could have suffered from reduced survival, the observed cases of mortality in this study seemed unrelated to the transmitter (Garrettson & Rohwer 1998). Winter survival of Northern Pintails did not differ between tagged and control individuals (Fleskes 2003). Cappelle et al. (2011) reported loss of signal for nine out of 47 harness-attached satellite transmitters within 3 days after deployment for Garganey *Anas querquedula* (1 out of 18), Fulvous Duck *Dendrocygna bicolor* (2 out of 3) and Comb Duck *Sarkidiornis melanotos* (4 out of 20). Signal loss may result from transmitter failure, and bird mortality was only confirmed in four of these cases. The authors speculated that this was related to stress induced by handling and capture. Other studies did not observe increased mortality shortly after release (e.g. Garrettson and Rohwer 1998). Linking long-term effects of transmitters to bird mortality is often difficult in the field.

Besides occasionally reported to increase mortality, harnesses have been found to affect behaviour of tagged birds. Disturbed behaviour shortly after tag deployment is reported regularly, involving increased maintenance behaviour and reduced foraging (Perry 1981; Pietz et al; 1993; Blouin et al. 1999; Glahder et al. 1997; Garrettson et al. 2000; Robert et al. 2006). In some studies these effects diminished over time (Glahder et al. 1997; E.K. pers. obs.), while they persisted in others (Perry 1981; Garrettson et al. 2000). In several cases, avoidance of water was observed, most likely due to loss of waterproofing capacity of the plumage caused by the harness, which may limit the access to food, reduce body condition and prompt (sometimes fatal) illness or starvation (Perry 1981; Garrettson et al. 2000; Kesler et al. 2014; E.K. pers. obs.). On the longer term, feather and skin abrasion may occur, especially on the bird's back (underneath the transmitter) or at the pectoral muscle where the harness goes under the wing (Perry 1981; E.K. and T.L. pers. obs.). These abrasions could potentially lead to infection of the skin or altered behaviour due to thermoregulation problems. It should be noted that most physical effects can only be observed when birds are recaptured or when transmitter effects are tested in captivity. However, as most captivity studies (e.g. Capelle et al. 2011; Nuijten et al. 2014) are relatively short term (1 - 2 months) and captive birds are often incapable of prolonged flight, it remains difficult to fully assess the negative effects of transmitters.

There is also evidence that harnesses increase the costs of migration. The shape and size of external backpacks (including presence of an external antenna) can greatly affect the drag during flight. An increased drag, rather than the mass of the device, may reduce the migration distance and the reserves of the birds upon arrival, as shown by computer simulations by Pennycuick et al. (2012). This is supported by Bowlin et al. (2010) who show that backpack attached geolocators on stuffed Common Swifts *Apus apus* increased drag and thus their flight ranges. Similarly, Hupp et al. (2015) found that Northern Pintails equipped with 12 - 20g satellite transmitters (1 - 3% of the bird's body weight (BBW)) in East Asia build up a delay of 7.7 days per 1000 km during their migration compared to birds that were only ringed. Higher energetic costs during flight are given as a likely explanation. In a recent study on Barnacle Geese *Branta leucopsis*, timing of migration of individuals equipped with GPS-loggers (35g, 2% BBW) was slightly delayed in the first stretch of northward migration when compared to individuals that carried lightweight (1 g) geolocators on their colour rings (Chapter 4). Blouin et al. (1999) speculate that the tag or harness may have contributed to the fact that none of the six satellite-tagged Greater Snow Geese *Chen caerulescens* in their study completed migration successfully (tag weight: 100 - 140g, 4 - 5% BBW). However, migration is not always affected, given the lack of any difference in timing of arrival at spring staging sites in Greenland White-fronted Geese equipped with dummy satellite transmitters (38 - 54g, 1.5 - 2.0% BBW; Glahder et al. 1997) and timing of arrival and departure at a fall staging site in radio-tagged Brent Geese *B. b. nigricans* (radio transmitters of 26 - 25g, 1.5 - 2.0% BBW; Ward and Flint 1995) compared to ringed-only individuals. It is likely that effects on energy expenditure or flight capacity are especially manifesting during the most energy-demanding migratory flights, as suggested also by the loss of three satellite tagged Garganeys during the last stretch of their migratory flight across the Sahara (12 g satellite transmitters, 3% BBW; Cappelle et al. 2011). During other activities the negative effects on energy expenditure are probably less, as shown by a study of captive Brent Geese where energy expenditure during activities other than flight was not affected by carrying a 35 g transmitter (2% BBW; Sedinger et al. 1990).

If backpacks have a negative effect on migration and the condition of birds upon arrival on their breeding grounds, this may have carry-over effects on the breeding success, additional to potential direct effects of devices on breeding effort. Backpack attachments have been found to affect clutch size and timing and propensity of breeding. Pennycuick et al. (2012) point out that lower energy height (a measure of energy reserves) in Barnacle Geese after spring migration may directly affect reproductive investment such as clutch size. Even though timing of migration in Brent Geese was not affected in a study by Ward & Flint (1995), return rates from the wintering grounds to Alaska were dramatically low (1 out of 62) and the one female that had returned with a transmitter did not breed, in contrast to 90% breeding initiation in colour-ringed females. Pietz et al. (1993) suggest that the significantly later onset of breeding and smaller clutches in radio-tagged Mallards compared to ringed individuals may have been related to the energetic consequences of a shifted time budget with less feeding and more preening and maintenance behaviour due to the radio-tag. Accordingly, Rotella et al. (1993) report that Mallards with harness transmitters nested two weeks later than birds with sutured-and-glued or implanted transmitters, although both groups could have been affected by the transmitter attachment. Barnacle Geese with GPS-loggers bred some days later than a control group carrying lightweight geolocators (Chapter 4). Blue-winged Teals captured and equipped with a backpack shortly before the breeding season failed to produce a nest twice as often as conspecifics with implanted devices (Garrettson & Rohwer 1998). Similarly, two Barrow's Goldeneyes equipped with a transmitter shortly before the onset of incubation abandoned the nest (Robert et al. 2006). In contrast, the Blue-winged Teals as well as most of the Barrow's Goldeneyes captured and tagged during incubation did continue breeding (Garrettson & Rohwer 1998; Robert et al. 2006). Mallards tagged during late incubation did not have lower brood or duckling survival than mallards with implanted transmitters (Dzus and Clark 1996). Finally, reproduction could be impaired by negative effects of harness-attached transmitters on pair bond, as suggested by a high proportion of unpaired tagged female Brent Geese (Ward and Flint 1995, Chapter 4).

In conclusion, although the weight of modern tracking devices is no longer the limiting factor for reducing negative effects of tracking devices, especially for larger birds, the device and the harness itself may still induce changes in survival and behaviour. These effects depend strongly on the device shape, the moment of attachment and probably also harness design, which can all be optimized to fit the study system. When aiming for long-term tracking of birds, devices need to be solar-charged, requiring external attachment. Unless the lifetime of tiny batteries will be greatly enhanced, which would enable less-invasive alternative attachment like attachment to leg rings, harnesses remain the only available attachment method for many species.

Abdominal implants

White et al. (2013) argue, based on a meta-analysis, that detrimental effects of implanted devices on birds are less severe than for external devices. This is supported by several studies in waterfowl. Direct comparison between implants with internal antenna and (anchored) backpacks in wild female Mallards revealed that individuals with implants experienced significantly less negative impacts on survival and reproduction (Paquette et al. 1997). Dzus & Clark (1996) compared the return rates of Mallards with harness-style backpacks and implants with internal antenna to their breeding areas and found a twice as high return rate for birds with an implant. However, in both studies the effect of implants is unclear since no untagged control group was included in the experimental design. A study with captive Blue-winged Teal, in which individuals with backpack, implant and no transmitter were compared, showed that birds with implants lost weight in the first week after surgery compared to both other groups, but had recovered by the second week. Blue-winged Teals with implants with internal antenna did not alter their behaviour, unlike birds with harness transmitters (Garrettson et al. 2000). In the field, Blue-winged Teals with implanted transmitters with internal antenna had slightly, but not significantly, higher survival over the course of a breeding season than birds with harness transmitters and were more likely to initiate a nesting attempt (Garrettson & Rohwer 1998).

An important impact of using implanted tags may be direct physical effects or mortality due to surgery. Korschgen et al. (1996b) describe the histological reaction of Mallards to implanted transmitters with external antennas and conclude that the mild to moderate air sac alterations they found did not cause any behavioural or physiological effects. Post-surgery survival of Spectacled Eiders *Somateria fischeri* equipped with implants with external antennas was found to be impacted by pH and hematocrit values of the blood prior to surgery. Birds with low pH, or extremely low or high hematocrit, had lower survival rates during the critical first five days after surgery (Sexson et al. 2014). Obtaining these values prior to surgery may help reduce the mortality rate. A paper describing the surgical procedure for implantation of transmitters in Canvasbacks *Aythya valisineria* reports no abnormal behaviour or increased mortality after implanting devices with internal antennas (Olsen et al. 1992). Hupp et al. (2006) reported no post-surgery mortality in Lesser Canada Geese *Branta canadensis parvipes* tagged with radio-transmitters with external antennas. Survival during their first year was similar to that of control individuals, although survival and return rates 2-4 years after tag deployment were slightly lower, potentially suggesting a subtle chronic tag effect. The feeding, maintenance and active behaviour of these tagged individuals was similar to that of unmarked individuals and there was no sign that implantation affected the frequency of agonistic interactions (Hupp et al. 2003). The implantation of satellite transmitters with external antennas in Common Eiders *Somateria mollissima* during incubation led to the abandonment of 11 out of 12 nests in a Canadian study, but 30% of the tagged birds were observed nesting in the following years. Furthermore, the tagged birds spent more time preening than colour-ringed birds and suffered a 20% decrease in survival during the first year after surgery compared to the control group (Fast et al. 2011). Limping was observed in some individuals, something which was also found by 1 out of the 6 Common Eiders in the study of Latty et al. (2016).

The lack of a harness and large external structures other than percutaneous antennas makes implanted transmitters the preferred tracking devices for diving ducks, such as eider species *Somateria spec.* and Harlequin Ducks *Histrionicus histrionicus*. Negative effects seem limited, but the difficulty with these seaduck species is that monitoring them post-surgery is often impossible. Brodeur et al. (2008) were faced with signal loss of most satellite transmitters with internal antennas implanted in Harlequin Ducks in the months after deployment, but argue that resightings of several individuals up to four years later, combined with normal body temperature measurements before signal loss, indicated that this problem was caused by transmitter failure rather than bird mortality. Only one case of mortality was confirmed in this study and occurred within a few days after implantation, likely as a direct effect of surgery. An analysis of Harlequin Duck survival in Alaska revealed that recapture rates did not differ between birds with and without implants with external antennas, and only an average loss of body mass of 15g was detected in the two weeks following the surgery (Esler et al. 2000). Implanted transmitters can cause a change in diving behaviour as was shown in Common Eiders (Latty et al. 2010). The descents and ascents of foraging dives were slower, and total dive durations were longer after implantation of transmitters with an external antenna than before. This may have been caused by muscle damage from the surgery, or by a biomechanical change affecting buoyancy or imbalance in these birds. The prolonged active phase of the dives may result in overall higher energy expenditure in tagged eiders, or force them to use different (e.g. shallower) habitats than untagged birds (Latty et al. 2010). Latty et al. (2016) also showed that implanted transmitters with external antennas affected bird health and physiology by a change in biomarkers up to 3.5 months after surgery. Although we did not find clear negative effects of implanted devices with external antennas compared with internal antennas, and no studies comparing the two, Hupp et al. (2006) suggest that chronic low grade infections from bacteria entering the body along the external antenna could potentially reduce long-term survival.

Subcutaneous attachments

Negative effects of transmitters placed under the skin are not often reported, which could be due to the low number of studies in our analysis that used this method. There is some evidence that subcutaneously anchored devices affect survival and reproduction of birds. In ducklings of Mallard and Gadwall *Anas strepera*, survival was lower for individuals equipped with subcutaneously anchored radio transmitters compared to an untagged control group (Amundson et al. 2010; Krapu et al. 2004; Pietz et al. 2003). The authors note entanglement as possible cause for lower survival, which was also reported for Harlequin Ducks (Bond & Esler 2008). Bakken et al. (1996) found higher surface temperatures around transmitters attached with subcutaneous anchors in Mallard ducklings, but did not find differences in energetic costs for thermoregulation between marked and unmarked ducklings. The reduction of short term survival rates of female Mallards of up to 23% in Paquette et al. (1997), which was only significant in one out of five study sites, indicated that tags attached with subcutaneous anchors may sometimes affect adult birds. Other studies using subcutaneous implants found no effect on short term survival of Lesser Scaups *Aythya affinis* (Brook & Clark 2002), Surf Scoters *Melanitta perspicillata* and White-winged Scoters *Melanitta deglandi* (Iverson et al. 2006) or on annual survival of Wood Ducks *Aix sponsa* (Hepp et al. 2002). Subcutaneous attachments have been found to negatively affect reproduction in some cases. Paquette et al. (1997) found female Mallards with subcutaneously anchored backpacks to spend less time on egg laying and incubation and to initiate fewer nests. Enstipp et al. (2015) found strongly altered behaviour in Long-tailed Ducks *Clangula hyemalis* with subcutaneous attachments, with increased preening behaviour and less time spent on the water, and two out of five individuals developed a bacterial infection at the site of attachment. Radio transmitters attached with prong and suture had no effect on reproduction in Wood Ducks (Hepp et al. 2002).

Neck collars

Neck collars with tracking devices are often used in large, long necked species, such as swans and geese. For these species, a neck collar can be more suitable than a backpack, as it diminishes the area over which abrasion and drag occurs, and lacks a harness which can be wrongly adjusted to the bird's shape and disrupts the plumage. However, as the weight of the tag is not positioned at the centre of gravity, this may become problematic for the bird when tags are relatively heavy (Kölzsch et al. 2016b). In general, we found that neck collars used in studies are lighter (in mass relative to the bird's body mass) than harness-attached or implanted tags (backpack vs neck collar: $t_{185, 33} = 8.26$, $p < 0.001$; implant vs neck collar: $t_{105,33} = 8.34$, $p < 0.001$). Although several studies combined the use of neck collars and backpack attachments (Blouin et al. 1999; Petrie & Wilcox 2003; Sheaffer et al. 2007), a proper comparison of effects is lacking. Blouin et al. (1999) report that none of the Greater Snow Geese equipped with backpack transmitters reached the breeding grounds in 1993 and 1994 (due to signal loss, natural mortality or being shot), while four out of 11 birds equipped with neck collar transmitters did reach the breeding grounds in 1995. However, these transmitters were also lighter than the backpacks and direct comparison of attachment methods could not be made.

Neck collars with tracking devices can alter bird behaviour in similar ways as harness-attached backpacks, but this seems to be a short-term effect. In a captivity experiment, Kölzsch et al. (2016) reported no difference in behaviour between Canada Geese equipped with neck collar transmitters or backpack transmitters, but both groups tended to spend more time preening and less time feeding. Increased preening behaviour was also observed in a study on captive Bewick's Swans *C. columbianus bewickii* with neck collar transmitters, but this effect had disappeared after 6 weeks (Nuijten et al. 2014). Short-term effects on behaviour were also observed in the field. Snow Geese equipped with neck collar radio transmitters spent 2-3 times less time foraging than the control group in the season in which they were tagged, but this difference had disappeared in the following season (Demers et al. 2003). Black Swans *Cygnus atratus* equipped with conventional neck collars were not affected in their behaviour compared to the control group (Guay and Mulder 2009).

Multiple studies report negative effects of neck collars on reproduction. Snow Geese equipped with neck collar transmitters showed a high rate of divorce from their original mate (Demers et al. 2003). In subsequent breeding seasons, they delayed nest initiation and had smaller clutch sizes (Bêty et al. 2003; Demers et al. 2003). Also Canada Geese with neck collar transmitters experienced a lower nesting propensity and nested later than the control group (Dieter & Anderson 2009). Delayed laying can be the result of delayed or slowed down migration caused by drag of neck collars during flight (Demers et al. 2003), but such an effect has not yet been proven.

Shorter-necked species seem affected more by neck-collars, although this has not specifically been studied. Older studies using neck collars with radio transmitters on various duck species (Wood Duck, Canvasback, Redhead *Aythya americana*) showed adverse effects on behaviour, survival and reproduction (Gilmer et al. 1974; Montgomery 1985; Sorenson 1989). As can be expected for shorter-necked species, ducks with neck collars can get their lower mandible stuck in the collar, which leads to retarded behaviour and sometimes mortality (Montgomery 1985; Sorenson 1989). Not only ducks experience problems with neck collars, but negative effects have also been found for shorter-necked geese. The relatively short-necked Emperor Geese *Chen canagica* experienced lower survival, lower breeding propensity, and laid one average one egg less when carrying a neck collar compared to a control group with leg rings (Schmutz & Morse 2000). Ross's Geese *Chen rossii* wearing neck collars were more vulnerable to being shot by hunters than birds marked with tarsal bands (Caswell et al. 2012). Feeding behaviour during winter was not affected in Brent Geese carrying narrow neck collars with radio transmitters (Hassall et al. 2001), but negative effects of conventional neck collars have been found on courtship behaviour (Abraham et al. 1983) and nesting success in this species (Lensink 1968).

A specific concern with the use of neck collars is that ice has been reported to accumulate on plastic collars under freezing temperatures (e.g. Fox et al. 2014). Formation of ice has in rare cases been shown to be fatal for birds (e.g. Zicus et al. 1983), although other studies showed no effect on goose behaviour (Madsen et al. 2001; Fox et al. 2014). There are no reports of ice accumulation on other types of tracking devices.

Other attachment methods

The effects of other tag attachment methods, like gluing a device onto feathers or rings, have not often been tested in comparative studies. Enstipp et al. (2015) compared tesa-sutured devices with subcutaneously anchored devices in Long-tailed Ducks, and found that while birds with tesa-sutured devices recovered more rapidly from alterations of behaviour, tracking devices were lost after 26 days on average. Effects of other attachment methods were reported in original tracking studies. Survival and (re)nesting of Wood Ducks carrying a radio-transmitter on a bibs, a piece of fabric hanging from the neck on the chest, was lower than expected based on earlier studies, which may be related to the transmitter attachment (Ryan et al. 1998). We are unaware of other experiences with waterfowl carrying bibs. More conventional are devices mounted to the tail feathers. Guillemain et al. (2002) glued and bound 3.5 g radio-transmitters to the central rectrices of five dabbling ducks species. One of 21 individuals was found dead three days after logger deployment, but this was likely unrelated to tag attachment. Similarly, radio-transmitters were glued and bound to the tail feathers of Mallard, Eurasian Teal and Northern Pintail in France by Legagneux et al. (2009), but no details are provided about whether or not this affected the birds. Seven out of 20 tail-mounted transmitters of 17 g in Barnacle Geese were lost prematurely in a study by Phillips et al. (2003), but no transmitter effects on the birds were reported. Reynolds (2004) cut a small patch of feathers on the lower back of Laysan Teal *Anas laysanensis* to glue radio-transmitters directly onto the skin and adhered them to uncut feathers with strips of tape. Also in this study, transmitter loss by detachment was frequent and the author did not report the presence or absence of effects on the birds. Miniature geolocators (light loggers) were attached to plastic leg rings of Barnacle Geese in a study by Eichhorn et al. (2006) and no effects on nesting or survival were reported. A peculiar tag attachment method was tested in canvasbacks. After particularly bad experiences with harness backpacks, Perry (1981) tested the attachment of radio-transmitters on Canvasback nasal saddles. Pilot studies on a limited number of canvasbacks in the lab and in the field were reported as promising and after a six-hours adjustment period the birds behaved normally. However, we are not aware of follow-up studies by the author or any more recent study using this attachment method.

Reporting of effects in primary tracking studies

Our review has revealed the wide range of potential effects that are associated with different tracking device types and attachment methods, but has also shown that many effects are still poorly understood. Full understanding of how tracking devices affect the behaviour and survival of waterfowl can only be obtained when these effects are studied and reported. No two tracking studies are carried out under exactly the same circumstances following the exact same procedure, hence every study can add knowledge on causes of effects and how they can be avoided. In order to identify how communication about tagging effects could be improved, we first analysed the reporting behaviour in current waterfowl tracking literature.

Eighty-four out of the 202 (42%) primary tracking studies in this review (Table S5.2) reported the presence or absence of an effect of the tracking methodology (Table 5.1). In only 18 of these 84 studies (21%) this was based on a comparison of the tagged birds with a control group. Other studies based this on a comparison of tagged birds with data of the rest of the population (36 studies), a comparison with birds tagged using another tracking method (7 studies), observation of tagged birds (6 studies) or did not clarify (17 studies). Of the 84 studies that reported whether or not there was an effect, two mention that tag effects were hard to distinguish from other factors, and 43 studies specifically mention that there was no effect. In the other 39 out of 84 studies, the reported tagging effect was considered negative (no positive effects were reported), corresponding to 19.3%

of the total of 202 studies. The number of studies that used control groups did not differ between studies that either did (9/39; 23%) or did not find negative effects (9/43; 21%). When distinguishing between studies that found minor effects (such as short term weight loss or behavioural changes lasting less than a few weeks) and major effects (directly impacting fitness via effects on survival, reproduction or migratory behaviour), we found that 34 out of the 39 studies reporting negative effects included major effects, which is 17% of the total of 202 studies. We broadly distinguished between effects on survival, reproduction and migration, and found that only one of these 34 studies discussed all three components (Hupp et al. 2006). Most of the studies only mention effects on survival and/or reproduction, while very few report effects on migration. Given the above described effects of transmitter-induced drag on the flight range of migrating waterfowl, this low report rate is unlikely due to a lack of effects but rather due to difficulties with detecting effects on migration. Since effects in wild birds can be difficult to detect in general, it is questionable whether studies explicitly claiming no adverse effects on their study species without the use of an untagged control group, used an appropriate study setup to detect such effects.

Table 5.1: Numbers and fractions (between brackets) of studies reporting effects of different types of tracking devices. The “reported” category includes all studies reporting whether or not an effect was found. The “control group” category includes studies (as a fraction of the studies that report) that contrasted the potential negative effects of tagged birds with a control group. Studies reporting adverse effects (“negative”) were split into studies which found only minor, short-term negative effects (only in the first weeks and not affecting survival, reproduction or migration) and studies which (also) found major, often long-term negative effects. The studies which found long-term negative effects were subdivided into studies reporting effects on survival, migration and reproduction if this information was provided. As in some studies negative effects were found in multiple of the above categories or were not specified, the total number of papers in these categories does not equal the number of studies that found negative effects. No studies reported positive effects of tracking devices.

	ackpack harness	implant	sub-cutaneous	neck collar	other	total
reported	45/112 (0.40)	25/59 (0.42)	6/14 (0.43)	9/23 (0.39)	3/6 (0.50)	84/202 (0.42)
control group	8/45 (0.18)	5/25 (0.2)	1/6 (0.17)	4/9 (0.44)	0/3 (0.0)	18/84 (0.21)
negative	22/45 (0.49)	9/25 (0.36)	1/6 (0.17)	6/9 (0.67)	1/3 (0.33)	39/84 (0.46)
minor negative	4/22 (0.18)	1/9 (0.11)	0/1 (0.00)	0/6 (0.00)	0/1 (0.00)	5/39 (0.13)
major negative	18/22 (0.82)	8/9 (0.91)	1/1 (1.00)	6/6 (1.00)	1/1 (1.00)	34/39 (0.87)
survival	7/18 (0.39)	5/8 (0.63)	1/1 (1.00)	2/6 (0.33)	1/1 (1.00)	16/34 (0.47)
migration	4/18 (0.22)	2/8 (0.25)	0/1 (0.00)	0/6 (0.00)	0 (0.00)	6/34 (0.18)
reproduction	8/18 (0.44)	3/8 (0.38)	0/1 (0.00)	6/6 (1.00)	1/1 (1.00)	18/34 (0.53)

Interestingly, the reporting rate of potential effects on birds carrying tracking devices seems to have changed over time. It was rather high until the early 2000s (65.0% of all studies reported the presence or absence of effects between 1981 and 2004), probably due to the novelty of using various techniques on birds. While more tracking studies were published in later years, this reporting rate dropped to 26.5% between 2005 and 2015. Of those studies in our review that did report potential effects, the fraction reporting negative effects remained stable over time around 51% (Fig. 1c). The reporting rate did not seem to differ between attachment methods (Table 5.1). Studies using neck collars appear to find negative effects more often than studies using other attachment methods (6 out of 9 studies found negative effects, Table 5.1), yet these used birds that are most easily identified and observed in the field. Most of the effects of neck collars and backpack attachments were found on reproduction, while studies using implants more often found effects on survival. Studies using subcutaneous attachment rarely found negative effects, but note the high loss rate of the tags and the low number of studies that used this method.

Towards reduction of adverse effects

Our review demonstrates that attaching tracking devices to waterfowl may lead to adverse effects on survival, migration and/or reproduction in any species. Not all tracking studies report potential effects, so it is difficult to assess why and how often such effects occur. Moreover, many studies did not include a control group in the study design, which hampers the detection of potential effects. When studies explicitly report a lack of adverse effects in their study population, the question rises whether this could be due to low sample sizes, which decreases the detection probability, or due to inadequate measuring of potential effects. Some studies with very low sample sizes did find large effects, indicating that some effects can be quite dramatic, while on the other hand, some studies with large sample sizes, thus having a high probability of finding effects, did not find any (e.g., 185 birds in study by Esler et al. 2000; 228 birds in Gaidet et al. 2010; 235 birds in Pietz et al. 1993). This would indicate that tracking waterfowl can be done without affecting the birds. By comparing the methodology of different studies and their reported presence or absence of effects, we should aim at identifying which tracking devices yield negative effects in which species, how they affect the bird, and under which circumstances these effects do and do not occur. This will be an important step towards further reduction of negative effects. In order to do so, it is essential that studies 1) report in detail on the methods used for tracking, and 2) measure and report the tracking device effects on the study species.

During our literature review we found that details concerning the attachment of tracking devices were lacking in many studies. Most often, studies were unclear in reporting and differentiating the number of birds that were equipped with (sometimes different types of) tracking devices and the numbers eventually used in the data analysis (43 out of 202 studies). Also, the sex and age of the tagged birds were often not reported (19 out of 202 studies did not report the sex), and some studies did not report the weight of the tracking device (12 out of 202 studies). In order to compare the used methods and assess which method would be best for a certain species, studies need to report the methods used for tracking birds to a certain detail. This information should be available in publications, but also in (open-access) databases where tracking data are stored, such as the Movebank Data Repository (Wikelski and Kays 2016). We propose a standard set of metadata to be reported for any tracking study on waterfowl:

1. **Tracking device**: type of positioning system (e.g., radio tracking, GPS, geolocation), type of transmitting system (e.g., satellite, GSM, bluetooth), producing company, dimensions and weight;
2. **Bird**: (sub)species, sex, age (at least differentiation juvenile / adult), body mass, initial sample size of tagged birds, sample size of birds from which data was used in the analysis, whether control group is used, marking method of control group, sample size of control group;
3. **Capture method**: location, date, period of the bird's annual cycle (e.g., breeding season, moulting period), catching method, handling time and other samples acquired;
4. **Attachment method**: type, material for attachment and combined weight of the attachment materials and the tracking device.

Measuring the possible adverse effects is essential when studying natural behaviour of birds using tracking devices. Even if adverse effects occur on behaviour that is not of direct interest for the study, these can still carry over in aspects of behaviour that are of interest. As an example, if birds fail to breed because they carry a tracking device, this will also have an effect on the timing of their autumn migration. When performing a tracking study, it is thus important to measure any possible adverse effects of the tracking device on the bird. Based on the studies used in this paper, as well as personal experience, we suggest that a first potential reduction in adverse effects can be managed by at least thoroughly reviewing the proposed methodology and measure them by adding a control group to the experimental design.

Reviewing earlier tracking studies on the same species is an essential first step before deploying tracking devices on a bird. Methodological studies, such as Roshier and Asmus (2009) and Cumming & Ndlovu (2011), can be very useful for this purpose. Studies on closely related species can be used, but subtle differences (also in environmental variables) can make species respond very differently to one attachment method. As an example, steel rings in a harness did not show wear in Barnacle Goose, but became rusty and likely broke when used in a harness in the closely related Brent Goose (A. Dokter, personal communication), as these geese spend more time in saline environments (Stahl et al. 2002). Experts in bird tracking often have experience with multiple species and can assist in evaluating what method would be suitable for which study species. To provide a first suggestion of what could be the most suitable tracking methods for waterfowl species included in our review, we have compiled an overview of how often negative effects were found for different attachment methods (Table S5.3).

When using a little known or unfamiliar attachment method or study species, it will prove very informative to perform a study in captivity before applying the tracking device on wild birds (e.g. Nuijten et al. 2014; Kölzsch et al. 2016b). This way, the potential effects on time budgets (e.g., time feeding, preening) can be studied relatively easily, as well as shedding of the tracking device or the possibility that birds become entangled by the attachment method.

When designing a tracking study on wild birds, adding a control group which is treated in the same way as the tagged group but which lacks the tracking device makes it possible to measure differences in behaviour and survival (e.g. Schmutz & Morse 2000; Reed et al. 2005). Marking birds in a control group with lightweight visual marks (metal and colour rings) is usually considered to be of little influence on the bird (Calvo & Furness 1992), while it enables later recognition in the field. Simple neck collars can probably be used for long-necked waterfowl without long-term effects, but have been found to affect reproduction and survival in some species (Lensink 1968; Schmutz & Morse 2000; Reed et al. 2005; Caswell et al. 2012), and should thus be used as a control with caution. A control group should be treated in the same way as the tagged group in as many aspects as possible, including the method of capture, other samples taken (e.g. blood samples), attachment of visual marks (metal and colour rings) and potentially also handling time (although the attachment of the tracking device may increase handling time substantially). Adverse effects can then be measured by observing both the tagged and the control group in the field. Not all possible adverse effects can be measured easily, as it is often difficult to track birds in the control group equally well as birds with tracking devices. This is particularly true for measuring effects on migration. For larger birds, it is sometimes possible to equip a control group with lightweight (<1 g) geolocators on the colour rings, which can be used to measure migration variables such as moment of departure and arrival, and migration speed (Eichhorn et al. 2006; Chapter 4). Yet, ring resightings and recoveries can also give useful estimates for comparison of some migration variables (Hupp et al. 2015), such as the moment of arrival (Both et al. 2016). Observing birds after release can reveal differences in behaviour and short-term survival between the tagged group and the control group. One year return rates (e.g., to the breeding colony) can give an indication of differences in annual survival, for which it is important to use the same observation method (i.e. visual observation) for both tagged and control groups. This will also enable estimation of the rate of transmitter failure, which helps to distinguish between signal loss and bird mortality. Effects on reproduction can be measured in multiple ways, including nesting propensity, nest initiation date, clutch size and hatching success. When possible, recapture of birds of the tagged group and the control group can give insights in physical effects, including body condition and physical damage as a result of the tracking device attachment (Esler et al. 2000). Finally, it should be evaluated and discussed by the authors of original tracking studies to which degree the potential tag effects are indeed negative within the context of the species' life history and ecology.

Conclusions

The primary aim of this study was to identify how attaching tracking devices on waterfowl may affect their survival, behaviour and reproduction, and explore how measuring and reporting of negative effects may provide directions towards reduction of these effects in future studies. Adverse effects on bird behaviour have been reported occasionally for all methods of attaching tracking devices, and there is not a single best method for all species. However, the occurrence and type of negative effects clearly differ for species and attachment methods, and based on earlier studies it is often possible to determine a suitable method for single species (Table S5.3). If any negative effects are still to be expected, these should be outweighed by the scientific benefits of the study, as is usually legally mandatory and should be assessed by an animal welfare committee. In recent years, very few studies on waterfowl reported potential effects of tracking devices, while the fraction of studies in which negative effects were found has not decreased. This is a worrisome trend which is also reported for studies on seabirds (Vandenabeele et al. 2011). When studying birds using tracking devices, it remains essential to determine whether their behaviour or fitness are affected, as this can greatly influence study results. We stress the importance of measuring effects of tracking device attachment on the behaviour and survival of birds to make sure that data on natural behaviour are collected. A promising way to reach broadly supported 'best practice' methods for tracking studies is to combine expert knowledge of waterfowl researchers with comparative observations in the lab and in the field. We hope that the use of a standardized format for reporting details of tracking methods will improve the exchange of information, and we encourage researchers to measure effects of tracking devices on fitness and behaviour by adding control groups to their studies. These data should be reported in publications, but also in (open-access) databases where tracking data are stored for future use. This will lead to better science and pave the way towards a reduction of adverse effects of tracking devices on waterfowl in the future.

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Supplementary material

Table S5.1 (Complete list of all 202 papers used for meta-analysis) can be found online: https://static-content.springer.com/esm/art%3A10.1186%2Fs40317-017-0139-6/MediaObjects/40317_2017_139_MOESM1_ESM.docx

Table S5.2: Information extracted from studies, including categories when used

Information	Categories
Year of publication	
Study species	
Sex studied	
Capture and tagging year	
Capture and tagging season	outside breeding season / during breeding season / during moulting
Method of attaching tracking device	harness backpack / neck collar / abdominal implant / subcutaneous implant / other
Type of tracking device	radio-transmitter / PTT / GPS-transmitter / geolocator
Weight of tracking device	
Weight of birds in study	
Number of birds tagged	
Number of birds used in analysis	
Was absence/presence of effects reported?	yes / no
Was an effect found?	yes / no
What was the direction of the effect?	negative / positive
Effect on survival	negative / positive / no effect
Effect on migration behaviour	negative / positive / no effect
Effect on reproduction	negative / positive / no effect
Physical effects	negative / positive / no effect

Table S5.3: Number of studies that report effects and number of studies that find adverse effects of attachment methods (underlined). Colours denote a "sensitivity" score for different species and attachment methods: green (0 – 33% of studies find negative effects), orange (34 – 66% of studies find negative effects) and red (67 – 100% of studies find negative effects). Note that in some cases this is based on only one study which reports (negative) effects.Supplemental Table S3: Number of studies that report effects and number of studies that find adverse effects of attachment methods (underlined). Colours denote a "sensitivity" score for different species and attachment methods: lightgrey (0 – 33% of studies find negative effects), darkgrey (34 – 66% of studies find negative effects) and black (67 – 100% of studies find negative effects). Note that in some cases this is based on only one study which reports (negative) effects.

Species	Scientific name	Backpack	Implant	Neck collar	Subcut-aneous	Other	Total studies	Specific effects
White-faced whistling duck	*Dendrocygna viduata*	2					2	Gaidet et al. 2008; Petrie & Rogers 1997
Tundra Swan	*Cygnus columbianus*	1 / 4					4	Klaassen et al. 2004; Beekman et al. 2002; Nowak et al. 1990; Nuijten et al. 2014
Brent Goose	*Branta bernicla*	4 / 5		1			6	Backpacks influenced survival (Ward & Flint 1995) and reproduction (Green et al. 2002; Green et al. 2002; Clausen et al. 2003); Gudmundur et al. 1995; Hassal et al. 2001
Barnacle Goose	*Branta leucopsis*	1				1	2	Kölzsch et al. 2015; Eichhorn et al. 2006
Canada Goose	*Branta canadensis*	1	1 / 3	1 / 1			5	Malecki et al. 2001; Hupp et al. 2003; 2006; 2010; Greater canada geese with neck collars nested less often and later (Dieter & Anderson 2009);
Emperor Goose	*Chen canagica*			1 / 1			1	Reduced survival, breeding propensity and lower clutch size (Schmutz & Morse 2000)
Greater Snow Goose	*Chen caerulescens*	1 / 1		3 / 4			5	High mortality for backpacks (Blouin et al. 1999), neck collars affected reproduction and pair bonds negatively (Demers et al. 2003); Bechet et al. 2003; Bêty et al. 2003; 2004
Bar-headed Goose	*Anser indicus*	1	1				2	Hawkes et al. 2012; Bishop et al. 2015
Pink-footed Goose	*Anser brachyrhynchus*	1					1	Glahder et al. 2006
Lesser White-fronted Goose	*Anser erythropus*	2					2	Aarval and Oien 2003; Lorentsen et al. 1998
Greater white-fronted Goose	*Anser albifrons*	1 / 4					4	Birds with backpacks departed and arrived later (Ackerman et al. 2006); Fox et al. 2003; Gladher et al. 1997; van Wijk et al. 2012

Table S5.3: Continued

Species	Scientific name	Backpack	Implant	Neck collar	Subcut-aneous	Other	Total studies	Specific effects
Long-tailed Duck	*Clangula hyemalis*		1 / 1		1 / 1	1 / 1	1	High mortality after surgery of implants (Mallory et al. 2006) and increased preening and infections by subcutaneous attachment and suture attachment (Enstipp et al. 2015)
Spectacled eider	*Somateria fischeri*		1 / 1				1	Birds with specific values for pH and hematocrit in blood are less likely to survive after surgery (Sexson et al. 2014)
King Eider	*Somateria spectabilis*		2				2	Bentzen & Powell 2015; Oppel et al 2008
Common eider	*Somateria mollissima*		3 / 4				3	Impaired diving behaviour (Latty et al. 2010), reduced 1st year survival (Fast et al. 2011) and evidence for long-term (at least 3.5 month) change in health and physiology (Latty et al. 2016); Petersen & Flint 2002
Stellers eider	*Polysticta stelleri*		2 / 3				3	Likely negative effects on survival (Martin et al. 2015; Rosenberg et al. 2014); Petersen et al. 2006
Black Scoter	*Melanitta americana*		1 / 1				1	Possible effect of cold winter on survival (Loring et al. 2014)
Barrow's Goldeneye	*Bucephala islandica*	2 / 2	1 / 1				3	backpacks reduced feeding and survival, possible effect on reproduction (Robert et al. 2006; 2010) females with implants left nests after surgery (Savard & Robert 2013)
Harlequin Duck	*Histrionicus histrionicus*		1 / 4		1 / 2		6	Possible negative effects on reproduction (Robert et al. 2008); Brodeur et al. 2002; 2008; Esler et al. 2000; birds entangled in subcutaneous attachment (Bond & Esler 2008); Bond et al. 2009
Egyptian goose	*Alopochen aegyptiacus*	1					1	Cumming & Ndlovu 2011
Wood Duck	*Aix sponsa*				1	1 / 1	2	Hepp et al. 2002; Possibly reduced breeding propensity by bibs (Ryan et al. 1998)
Canvasback	*Aythya valisineria*	1 / 1	1				2	weight loss and feather wear (Perry et al. 1981); Olsen et al. 1992
Redhead	*Aythya americana*			1 / 1			1	Negative effects on reproduction and survival (Sorensen 1989)

Table S5.3: Continued

Species	Scientific name	Backpack	Implant	Neck collar	Subcut-aneous	Other	Total studies	Specific effects
Lesser Scaup	*Aythya affinis*				1		1	Brook & Clark 2002
Northern Shoveler	*Anas clypeata*					1	1	Guillemain et al. 2002
Blue-winged Teal	*Anas discors*	2 / 2	2 / 2		1 / 1		5	Backpacks affected reproduction and behaviour, birds with implants abandoned nests and lost weight in the first week (Garrettson & Rohwer 1998, Garrettson et al. 2000); birds became entangled in transmitter (Gue et al. 2013)
Gadwall	*Anas strepera*				1	1	2	Guillemain et al. 2002
Mallard	*Anas platyrhynchos*	6 / 10	1		2	1	14	Negative effects on reproduction (Losito et al. 1995; Pietz et al. 1993; Paquette et al. 1997), decreased body condition (Dugger et al. 1994; Kessler et al. 2014) and survival (Dzus & Clark 1996); Davis et al. 2011; Hagy et al. 2014; Kesler et al. 2014; Van Toor et al. 2013; DeVries et al. 2003; Gue et al. 2013; Pietz et al. 1995; Guillemain et al. 2002
American black duck	*Anas rubripes*	1 / 2					2	Worn feathers and calluses on back in tagged birds (Longcore et al. 2000); Parker 1998
Red-billed Teal	*Anas erythrorhyncha*	1					1	Cumming & Ndlovu 2011
Northern Pintail	*Anas acuta*	2 / 4			1	1	6	Negative effects on migration speed and survival during migration (Hupp et al. 2011; 2015); Fleskes 2003; Miller et al. 2005
Common Teal	*Anas crecca*					1	1	Guillemain et al. 2002