# Why catch when you can throw? A framework for tagging animals without capture or restraint

**Rory Wilson** (rorypwilson@swansea.ac.uk)
Swansea University
**James Redcliffe**
Swansea University
**Mark Holton**
Swansea University
**Victoria Thomas**
Swansea University
**Richard Gunner**
Max Planck Institute of Animal Behavior
**Vaclav Silovski**
Czech University of Life Sciences Prague
**Milos Jezek**
Czech University of Life Sciences Prague
**Holly English**
University College Dublin
**Olivia Shott**
Swansea University
**Katie Bambridge**
Swansea University
**Elliot Dee**
Swansea University
**Hazel Nichols**
Swansea University
**Flavio Quintana**
CONICET,
**Andreas Fahlman**
Kolmården Wildlife Park
**Josefin Larsson**
Kolmården Wildlife Park
**D. Michael Scantlebury**
Queen's University Belfast
**Ursula Siebert**

University of Veterinary Medicine Hannover, Foundation

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# Abstract

**Background:** The attachment of electronic tags to animals has led to data collection that has hugely enhanced our understanding of wild animal behavioural ecology and physiology. However, animals are normally captured and restrained/sedated so that the tags can be attached, which is stressful for the animals and threatens to compromise the quality of the data gathered, at least during an initial acclimation period. We note that many plant seeds have evolved to become attached to passing animals and suggest that an approach, based on plant burs, could be used to attach tags to animals without capture or restraint.

**Methods:** We present a framework for ‘bur-tagging’ and provide details of the design of a bur-tagging system, highlighting issues that we feel should be considered for the approach to be successful.

**Results:** We report how the tagging site in the environment and animal neophobia critically affect the probability that an animal will be tagged over any given time period and also document what needs to be done to ensure that only the target species is tagged as well as illustrating the steps that can be taken to enhance the accuracy of tag placement on the animal. In addition, we discuss the criticality of the choice of the adhesive mechanism between the tag and the animal and illustrate how animals react to being tagged using this system.

**Conclusion:** Although in an early stage of development, we believe that ‘bur-tagging’ shows great promise for deploying sophisticated electronic tags on wild animals with less stress than the conventional capture and restraint approach.


# Introduction

The deployment of tags on animals has become a sub-discipline within zoology in its own right (often termed ‘biologging’ or ‘animal biotelemetry’). It has progressed from the use of simple VHF systems in the 1960s (*1*) to the hugely sophisticated transmission and logging systems used today (*2*) that can record ‘big’ data simultaneously from multiple sensors, such as accelerometers, magnetometers, pressure and temperature sensors (*3*), as well as from microphones and cameras (*4*). These tags not only provide unprecedented detail on the movements, behaviours and energy expenditures of individual animals (*5*) in addition to documenting details of the animal’s environment (*6*) and recording physiological function (*7*), but are now being used in such numbers that researchers are rapidly moving towards using data from them to examine ecosystem functioning (*8*) and how physiological limitations may curtail survival and help guide conservation efforts (*7, 9*). Indeed, the potential of animal-attached tags for understanding fundamental and applied issues in wild animal behavioural ecology (*4*) and eco-physiology (*7, 9*), is such that tens of thousands of tags are deployed across the globe every year.

However, almost without exception (but see (*10*)), these tags are placed on (or in) the carrier animals after capturing them (*11, 12*), either by trapping them and/or by using sedatives (*13*). This process causes considerable stress, both physiological and behavioural (*13 and references therein*), affecting animal wellbeing and influencing the scientific value of the results. Given that a major prerequisite for deploying tags on wild animals is that it should maximize welfare anyway (*13*), there is obviously a need to optimize best practice for tag deployments (*14*). Although there is much literature on how to do this within the 'animal capture and restraint' (CaR) model of tag deployment (*15*), we suggest that it should now be possible to deploy tags onto study animals without CaR. Instead, we propose that tag deployment can be effected by an automatic tag dispenser that releases the tag onto the passing animal, at which point the tag should adhere for a defined period, providing useful data without CaR. In support of this general approach, we note that a large variety of plants actually disperse seeds – termed burs – using this method (*16*) so we accordingly call our proposition 'bur-tagging'. Indeed, given the extraordinary miniaturisation of animal-attached tags, the viability of bur-tagging follows as an almost logical consequence.

In this work, we provide an initial framework for bur-tagging based on research that attempts to quantify the major elements that affect the success of this approach. Our work is intended to provide an overall holistic approach to bur-tagging rather than provide a single solution because, as we note, different animals require different solutions to the various facets of the framework. We believe that, once embraced and refined by the community, it could lead to a game change in the value of data and in the wellbeing of the study species for animals equipped with tags.

# Methods

### The Bur-tagging framework

As simple as the bur-tagging concept is, there are a number of fundamental issues ranging from maximizing the probability that the study species will encounter the bur-tagging system (BurTS) to neophobia to the BurTS that determine its likely success. We consider these elements below

### A blue-print for a Bur-tagging System (BurTS)

Any BurTS needs to ensure eventual contact between the study species and the tag. The simplest form of BurTS then consists of the tag attached to the end of a protrusion, such as a straw, that the animal brushes past during normal movement. The adhesive properties of the tag then lead to successful deployment (Fig. 1A). This approach is used by ticks (*17*) as well as plant burs but necessitates that large number of tags be deployed, only operates over a short range and is relatively unselective in which species might be tagged. Consequently, we concentrated on a BurTS that consisted of an animal sensor mechanism linked to a tag dispenser, which could propel the tag, all controlled by simple software (Fig. 1B). The sensors help refine which species are likely to be tagged (see section 'detection of target animal' below) while the tag dispenser could allow the tag to reach the target animal even over distance (see section 'accuracy of tag placement' below).

After consideration of a number of sensory systems, ranging from pressure sensitive plates, trigger sticks, through infra-red sensors to lasers, we concentrated our BurTS sensor approach on ultrasound sensors

(Fig. 1D - SI 1) although different sensor systems may work better for different target species. Ultrasound sensors are small, relatively inexpensive, can be set to operate over different distances, and can be used in number to filter out unwanted species (see section 'detection of target animal' below). In order to have a fairly standard system that we could use to test for animal reaction to the BurTS, we attached sensors, tag dispensers and control box (Fig. 1D, Supplementary Information 1) to a single frame, shaped in the form of an inverted 'U' as is typical of a Japanese Gate (Fig. 1C, Supplementary Information 2). From hereon, we refer to the BurTS in this configuration as the 'Japanese Gate'. In brief, when both ultrasound sensors were triggered, the control board activated the tag dispenser to release the tag, projecting it in the direction of the animal (Supplementary information 1-3).

### Maximizing the probability of animals encountering the BurTS

There is a rich literature on how the placement of camera traps affects the likelihood of detecting certain species (*18, 19*), much of which is directly applicable to the BurTS. However, somewhat in contrast to camera traps, which seek to scan a relatively large area, for a successful tag deployment, our target animal must move within a very well defined space (see section 2.5). For our purposes, we define that space as the animal being in a position where the sensors within the BurTS would normally initiate tag deployment.

The probability that the study species encounters the BurTS per unit time in this way ($P_T$) is critical because, all other things being equal, this probability affects the expected deployment period before a likely tagging. This can be approximated by standard probability theory whereby the overall probability of an animal being tagged over time;

$P_{Tag} = (1-(1-P_s^t))$ (1)

where $P_s$ = the probability that the animal will be tagged within a defined time period, and t is the period over which the BurTS is deployed. Importantly, small changes in $P_s$ result in large changes in $P_T$ with time (Fig. 2.2A), particularly when $P_s$ is low (Fig. 2.2B). Thus, any information that results in placement of the BurTS at a site with increased traffic by the target species, such as well-used trails in the right vegetation type, habitat and topography, is particularly important.

Deploying cameras (Supplementary Information 4) to examine the extent to which our placement of BurTS affected target animal detection (including appropriate proximity to the BurTS to allow tag deployment) [a total of 304 camera days at 20 sites], showed the importance of expert advice in identifying frequently used areas (*20*) due to the substantial variation in the rate of animal/BurTS encounters with site. For example, over a period of <1 week [period chosen to diminish the effects of neophobia – see section 'the role of neophobia' below], camera-based assessment of European badger *Meles meles* interaction with the BurTS showed that badgers were more often associated with 'well-defined trails' than sites where no trail was visible ($\chi^2$ = 6.37, P<0.02, df = 1) although Red Foxes *Vulpes vulpes* showed no significant difference in their usage of 'faint' versus 'well defined' trails ($\chi^2$ = 0.12, P>0.05, df = 1). Given the importance of maximizing $P_s$ (see above), we would advocate the use of camera traps for sites being considered to help identify well-used sites before deploying the BurTS.

Normal animal traffic at certain sites can also be increased, thereby increasing $P_s$, for some species, by selective baiting (*21*). For example, we noted a significant increase (GLMM F = 9.92, P <0.005) in the number of Red Foxes moving through the Gate when it was associated with baiting (Supplementary Information 5 – Supplementary Film 1). Baiting does complicate matters though because, if the bait is close to the gate, animals may not move through uniformly and perpendicular to the gate (which are ideal conditions for accurate tag deployment). Conversely, placing bait at distance from the gate can dissuade animals from moving through it at all. We suggest that the ideal circumstances to use bait are when it is placed along a trail at some distance from the BurTS and either side of it so that the trail-using animal may deviate from normal locomotion due to the bait but then adopt more normal travel as it moves between baited spots.

## The role of neophobia

We found that neophobia, the fear of, or aversion to, unfamiliar things (*22*), played a substantial role how animals reacted to the BurTS and therefore in the probability of a target animal being tagged by the BurTS. This is expected to vary with species (*23, 24*), situation (*25*) (including personality (*26*), age (*27*) and cognitive abilities (*28*)) and exposure time. Our camera trap work where we documented animal reaction (broadly grouped into apparent 'attraction', 'indifference' and 'repulsion') to two versions of the Japanese Gate illustrated some of these predictions (Supplementary Films 2-4). For example, there was a significant decrease in the number of interactions (both attraction and repulsion) of European badgers with the Japanese Gates over time (Fig. 3A), though not in Red foxes (Fig. 3B) and, importantly, the probability that both species would move through the Japanese Gate also increased significantly with time (Fig. 3C, D).

The specific form of the decrease in interest of time, and the effective corollary of this, the increase in the likelihood per unit time that an animal will move appropriately into the active area of the BurTS ($P_s$ in equation 1), is important for predicting how long it will take before there is a reasonable chance that a target animal will be tagged (Fig. 2). Also, pragmatically, it indicates how long dummy bur-tagging systems should be left out before being loaded with tags: Many tags use power to function and there is little point in wasting battery life for a tag that is not deployed, unless a trigger mechanism is installed to turn the unit on at the point of deployment.

Our work highlighted significant differences between species (*23*), and we would also expect animals to react according to the extent of the footprint of the Japanese Gate, with animals being less neophobic to smaller and more natural gates. Our trials comparing wooden to aluminium Japanese Gates in this regard were, however, inconclusive, primarily due to us being unable to standardize exposure conditions. However, studies at zoos indicated how the height of the cross bar in the Japanese Gate affected the response of target species, at least those species that do not habitually move through holes in the vegetation. For example, Capybaras *Hydrochoerus hydrochaeris* were notably more perturbed by low-set bars than by high-set bars (Supplementary Films 5 and 6). So, apart from being aware of how species- and situation-specific neophobia affects the chances of successful tagging, researchers need to appreciate how the precise construction of the BurTS footprint might affect the chances of tagging. Our initial construction of the Japanese Gate was intended to allow for flexibility because the height and width of the gate could be easily varied, as could the positioning of the ultrasound sensors, with the particular application being designed for mammals that push through holes in the vegetation (Fig. 1C). However, given that the greater the footprint of the BurTS, the more avoidance it is likely to evoke, we would recommend that the sensors and the tag dispenser be linked by minimal structure, and placed within the environment as inconspicuously as possible by, for example, attaching them to vegetation. For example, the battery to power the system can be placed some distance away, with the linking cable being buried. Tests of such a minimalist system on wild Red Deer *Cervus elaphus* by attaching both sensors and tag dispensers to trees showed it worked well (see section 'detection of target animal' below). As part of general reduction in BurTS footprint, it is germane that any BurTS be deployed by researchers wearing gloves since this reduces the unusual olfactory signal in the system (cf. *29*).

## Detection of the target animal

During deployment of our BurTS, multiple species were expected to interact with it and this was confirmed by our field trials. For example, during 304 days of deployment of the BurTS at 20 sites in Wales, our camera traps indicated that 194 individuals from 6 different vertebrate families (birds, carnivores, mustelids, squirrels, rodents and hedgehogs, in addition to domestic animals) interacted with it. These interactions ranged from the animals simply looking at the system (29% of interactions), pausing (30% of interactions) and sniffing it (41% of interactions). Overall, about 30% of animals appeared attracted to the BurTS while 20% appeared repelled. Finally, 74% of the individuals walked through the Japanese Gate while 26% did not. The diversity of animal species showing 'interest' in the BurTS, and the high percentage that walked through the Gate, illustrates the potential for tagging the wrong animal unless measures are taken to filter them out.

Although our BurTS was modified during the course of the work, we initially identified the necessity of having at least two sensors to determine the directionality of the animal, which is important to ensure that the tag is deployed at the correct spot on the animal (see section 'accuracy of tag placement' below). However, because the sensors are also important for precluding tagging of non-target species, the more sensors are used, the more the process can be refined. Our normal software for deploying tags in our standard BurTS application (section 2.1, Supplementary Information 3) simply dispensed the tag when both ultrasound sensors were triggered. Obviously, in this case, aside from the detection cone of the sensors, the height of the two sensors above the ground codes to some extent for the length and height of the target species and this needs to be set up carefully (Supplementary film 7). However, even this cannot preclude similarly sized species. Against this though, experiments with multiple ultrasound sensors demonstrated clearly that the side dimensions of animals could be well defined by a vertical placed array of sensors, more so if the software incorporated detection of the animal speed by having two sets of sensors placed horizontally (Fig. 4A). Finally, since ultrasound sensors can be programmed to record a positive signal (that an animal has been detected) over variable distances (e.g. 0.2-2 m - ELEGOO sensor data), some element of body width can be programmed into the software to further refine discrimination of the target species. There is though, a substantial caveat to this relating to the sensitivity of ultrasound sensors in general. The sensors work by generating a sound pulse which is beamed at the animal and then listening for the reflection (*30*). We ascertained that it is simplistic to assume that all animals reflect such sound waves equally. Specifically, our work with pelts from various species across different mammal families testing ultrasound sensor operation distance nominally set to 25 cm, showed substantial variation (Fig. 4B). This means that researchers wishing to use ultrasound sensors within BurTS should check ultrasound reflectivity of their target species before taking systems to the field.

The ability of the sensor system to differentiate the target species from any others will depend too on the specifics of the sensors. We concentrated our work on ultrasound sensors but others could be used in a similar manner, or different sensor types could be combined (such as weight platforms together with ultrasound). The future is likely to see more sophisticated discrimination still, using AI, which already has the capacity to discriminate between individual humans (*31*) and so might be able to differentiate between the sexes or even ages of the target species.

## Accuracy of tag placement on the target animal

Our prime BurTS consisted of two sensors to enable us to have a system that would put the tag in the correct place on the animal. At least two sensors are necessary for this because without it, it is impossible to determine the animal's direction of travel. Here, the distance between the sensors and the tag dispenser nominally determines the spot on the animal where the tag will be deployed: The distance between either of the sensors and the tag dispenser should be equal to the distance between the first sensor to react to the animal as it passes the BurTS and the ideal tag spot (Fig. 5).

We propose that an ideal tagging spot on the target animal is between the shoulder blades because this site is/appears most onerous for the animals to groom but also, for the increasing number of tags incorporating accelerometers, a site that is a good approximation of the body centre is most useful (*32*). With that in mind, our tag dispenser was generally placed above the centre line of the animal, as expected from the normal animal trajectory through the Japanese Gate. However, for our tests with long-necked animals such as Bactrian Camels *Camelus bactrianus* and Red Deer, we placed the dispenser slightly off-centre to allow enough space for the head to pass next to/underneath the dispenser without overly extending the distance between the dispenser and the back because this compromises the accuracy of the tag placement (see below).

Two basic dispenser concepts were explored, a simple passive drop and powered projection of the tag. In early work, we discovered that the simple drop took too long for the tag to reach the animal (depending on the distance covered – a function of Japanese Gate height relative to that of the animal subject), being especially sensitive to animal speed past the BurTS (see equations 2-6 below). For example, badgers moving through the Japanese Gate did so at speeds estimated to range from 0.05 to 0.6 m/s.

For a typical drop duration of 0.5 s, this effectively results in the tag landing either between the shoulder blades, as hoped, or, in the worst case scenario, actually landing behind the badger! We thus subsequently focussed attention on powered tag deployments noting, however, that the force used by the projecting system can also be varied to suit needs.

Although there are many ways of producing a force that will project a tag, we experimented with two systems; rubber- (catapult style) and spring-powered, and within-dispenser tag trajectories that were either open or barrelled/constrained by rails. Initial work with the 'rubber' and 'open' systems rapidly revealed unacceptable levels of tag trajectory variation. Such elastic systems are also likely to be non-ideal for deployment in the wild for extended periods due to material fatigue over time (*33*) which changes the projecting force (*34*). The use of compression springs proved convenient and flexible because they do not suffer from on-load material fatigue in the same way as rubber. In addition, springs can easily be selected on a case by case basis (depending on the distance to be covered and the likely target animal speed etc) to provide particular standardized forces (*35*). Finally, compression springs lend themselves to applying unidirectional force to a tag moving down a barrel (or a system on rails) to minimize the error in the trajectory of a tag (Fig. 6A). For example, the use of one of our standardized spring systems pushing a tag (of mass 7.4 g) down rails of 92 mm, rapidly powered the trajectory of a vertically released tag to 2.9 m/s (Fig. 6B) giving a mean path error of 4.58 (SD 1.79) (Fig. 6C), markedly lower than a comparable rubber-based system. However, it was notable that the errors using this system were not distributed evenly around a centre spot (e.g. Fig. 6D).

Knowledge of the time taken for the tag to be accelerated to its release, the speed of the tag on release and the distance between the tag projector and the animal on release, can be used to calculate how far behind the ideal tagging spot (Fig. 5) the tag will land as a function of the speed of the animal. In the example shown in Fig. 6, the acceleration phase of the tag lasts 0.35 s so, an animal travelling at 0.1 m/s with its shoulders at a distance of 0.1 m below the tag release spot will have the tag landing some 38 mm behind the ideal spot. This however, increases to 520 mm if the animal is travelling at 1 m/s and the distance between the animal and tag release spot is 0.5 m. This illustrates the important interplay between choosing a distance between tag release spot and the target animal that minimizes that error given the likely speed of the animal and the force imparted by the spring while at the same time minimizing animal stress due to the proximity of the tag dispenser (see section 2.3). In addition, researchers need to be aware that, although increasing the force imparted by the spring can dramatically increase the release speed of the tag, it is also likely to startle the animal more when the tag makes contact with it (see section 'reaction of animals to tag deployment' below).

Non vertical tag trajectories may be required for placement of tags on animals that have long necks, such as deer (see Fig. 1B), which would otherwise necessitate that the tag dispenser be placed high above them, ultimately resulting in too great an error in trajectory (e.g. Fig. 6C, D). Under such circumstances, the principles of kinematics can be used to approximate the tag's path assuming negligible air resistance. Knowing the release velocity of the tag ($v_0$ – in m/s), the initial horizontal velocity ($v_0x$) is given by;

$v_0x = v_0*\cos(\Theta)$ (2)

where Θ is the launch angle (in radians). The initial vertical velocity ($v_0y$) is;

$v_0y = v_0*\sin(\Theta)$ (3)

The total time the tag is in the air (T) is given by;

$T = 2* v_0/g$ (4)

where g is the acceleration due to gravity (*ca*. 9.81 $m/s^2$) and the horizontal distance (d) of the tag is given by;

$D = v_0x*T$ (5)

while the equation describing the trajectory of the tag (y as a function of x) is given by;

$y = x*\tan(\Theta) – (g*x^2)/(2*v_0^2*\cos^2(\Theta))$ (6)

Thus, knowledge of the initial velocity of the tag together with the tag projection angle, the vertical distance between tag dispenser and animal and some measures of system error (e.g. Fig. 6C,D) can go some way to predicting how closely the tag will land in the ideal position.

Attempts to maximize the accuracy of the tag deployment can also benefit by considering the extent to which the position of the BurTS occurs with constrained animal paths. For example, animals moving through a small hole in a hedge generally have their bodies perpendicular to the hedge with very constrained position, which is ideal for minimizing the distance between the tag dispenser and the animal, thereby increasing the accuracy of tag placement. For animal trails that may be less constrained, the addition of vegetation 'constrainers' may also help.

Finally, researchers need to consider the orientation of the tag during its trajectory between the tag dispenser and the target animal. Unsurprisingly, our work showed that tags tended to rotate more as the distance between the tag dispenser and animal increased, although weighting the tags so that the leading surface was denser that the trailing surface reduced this incidence markedly. A simple solution to this is to use tags where deployment orientation is not critical, noting that even accelerometers can be corrected for non-aligned placement *post hoc* in appropriate software. Under such circumstances, tags should be covered on all sides by their adhesive.

## Adhesion between tag and animal

From the moment that the tag contacts the animal until the moment it falls off, the adhesion between tag and animal is critical. So, both the strength of the adherence, which can be simplistically described by the force required to remove the tag, as well as how that might vary over time are important. This is dependent on the attachment mechanism used by the bur tag (*36*), the properties of the fur of the target animal (*37, 38*), the environmental conditions at the time of attachment, the propensity of the target animal to groom the tag off (*39*) and the site of attachment (which affects both the properties of the fur and the motivation of the animal to groom it off). We examined the first two of these, noting that the variability in the latter elements will be substantial depending on the target species.

There are many mechanisms used by plants to ensure that their fruits adhere to carrier animals (*36*), the two principle ones being hooks or viscid outgrowths (structures that secrete sticky substances). We attempted to simulate the adherence properties of both these by creating an adhesive pad stuck to the tags that; (i) simulated the physical structure of natural burs, (ii) used a tacky glue (*40*) and (iii) used natural burs. To do this, we standardized a tag-animal interface consisting of a specific area of plastic, onto one side of which various hooks and protrusions were attached. This interface was then stuck to dummy tags of defined mass which were then either applied (vertically down between the shoulder blades of animal pelts) with a constant force (by using a defined weight) to give a constant pressure (Fig. 7A), or projected onto various animal furs using the tag dispenser using a defined projection speed and distance. In tandem, we defined some of the properties of the animal furs used in our tests (between the shoulder blades) in an attempt to understand how fur properties related to adhesion. For this, we measured hair diameter at a point half way along the hair length [using a micrometre] and air layer thickness of the fur using a ‘featherometer’ as described in Ainley & Wilson (*41*) between the shoulder blades of animal pelts. Briefly, the featherometer applies a standard pressure to the fur and then measures the distance between the pressure application plate and the skin.

For any given fur type, we noted the importance of adhesive pad structure (Fig. 7B) in affecting the forces needed to dislodge the tag. However, in addition to the physical details of the structures responsible for the adhesion (e.g. barb length, hook radius etc.), forces were also dependent on structure density, with adhesion increasing non-linearly with structure density only up to a certain point (Fig. 7C).

Aside from the variation in the tag removal forces, which depended on the precise orientation of the hooks and the way they interacted with the fur (Fig. 7C), the higher densities of hooks probably have their penetration into the fur impeded for a given application force. We would, however, expect this to vary depending on the cross-sectional surface area of each hook, with smaller hooks, as are typical of plant burs (*42*), penetrating more easily.

So far, natural burs from Burdock (*Arctium lappa*) have necessitated much higher forces for their removal (by a factor of about 5 – e.g. the force to pull a Burdock bur directly off synthetic fur was 7.2 N (SE 0.25)) than any of our synthetic pads (see below). However, it proved impossible to standardize the above force-measuring protocol using natural burs since, by applying the necessary force, many of the bur hooks were removed, negating the pad for another trial. In addition, reconstitution of bur-based adhesive pads was difficult to standardize in the same way as our synthetic adhesive pads.

The forces needed to dislodge our synthetic adhesive pads depended on the direction that the force was applied (with the fur, against the fur, or perpendicular to the fur) (Fig. 8A), with higher dislodgement forces in a given pull direction tending to be mirrored by higher forces in another direction (Fig. 7A). These dislodgement forces also varied greatly with species (Fig. 7B,C) which was partly explained by a positive relationship with the air layer thickness of the fur (Fig. 7B).

There was no relationship between these forces and fur hair diameter ($P>0.05$) and both fur hair diameter and fur air layer thickness showed extensive variation between species (Figs 9A, B).

All this points to the complexities of bur-type attachment processes between plants and animals. Aside from our own measurements (see above), precise measurements of adhesion forces of some burs are substantial. For example, Gorb & Gorb (*42*) measured separation forces of between 3.3 and 144 mN per individual hook within burs (using 4 plant species) and noted that, since between 5 and 21 hooks may be involved in binding the fruit to the animal, this equates to total adhesion forces of up to 3 N (*42*). But these are also presumably dependent on the mammal species used due to differences in the properties of the fur (e.g. Fig. 9A,B), including in the microstructure of the hairs (*43, 44*). Certainly, studies report that animal hair length affects the number of bur seeds attached (*38*), which helps explain why our measured adhesion forces were greater in furs that had a thicker air layer (Fig. 8B) (which will presumably be greatest in animals with longer haired fur). Overall though, seemingly irrespective of which type of adhesive pad is used, we should expect animals in temperate or polar regions to provide a better adhesion to penetrating bur-based tags than animals in hotter climes (*45*). But inter- and intraspecific variation in the adhesive qualities of our various pads pointed to the intricacies of designing an optimal and long-lasting bond between tags and animals.

Our work with tacky glue was extremely limited, but demonstrated its potential for bur-tagging, particularly when used with hooks. Tacky glue is used to great effect by plants and that secreted by *Pisonia garndis* associated with their seeds is so effective at binding to seabirds that individuals over-burdened with the burs cannot remove them and die (*46*). We therefore have no doubt that continued research on tacky glues for bur-tagging can produce a step-change in tag-animal binding, particularly if combined with hooks/barbs (see above).

Overall then, our work illustrates that appreciable forces can be developed for adhesion between tags and fur, either by using synthetic adhesive pads based on hooks and tacky glues or, particularly, by using the burs themselves. However, much more work is needed in this complex area to be able to propose a general solution and how this might be modified according to the properties of mammal fur. Tag size and mass will also play a critical role here. Since force = mass X acceleration, high tag masses (cf. *42*), particularly if coupled with high animal accelerations (*47*), will increase the forces acting to remove the tag and consequently the likelihood that the tag will fall off. Similarly, large tags may be more easily groomed off or pushed off in animals that move through thick undergrowth.

We believe, at the moment, that the best adhesion between tags and their carrier animals will be provided by natural burs, which have had years to adapt to their hosts effectively. These natural burs can be cut in half and stabilized with glue before being stuck to the tag. Disadvantages of this approach are that they can only be used when they come from the target animal’s environment (to obviate unwanted species translocation), and natural burs are intended to fall off the carrier animal after a certain time anyway (*36*) although ‘weak spots’ to realise this can be stabilized with glue. The ability of bur tags to stay on their target animals for longer durations increases their usefulness although, if they can be applied involving the same stress to the carrier animal as a natural bur, it could be argued that even short deployments provide useful data. This is not the case where animals are sedated to attach tags (*13*). Ultimately, assuming that the target animal does not groom the tag off, and that an excellent bond can be formed between tag and animal (equivalent to, or based on, chewing gum, for example (*48*)), the maximum on-animal life of the tag could run into several months, and will be determined by the moult, which is highly variable between species (*49, 50*).

### Reaction of the animals to tag deployment

Although we believe that remote application of tags to animals will stress them less than standard capture and/or restraint/sedation processes, burTS study subjects experience neophobia (see above), which will likely influence their affective state and presumably make them more susceptible to other elements of the bur-tagging process such as the sound of the release servo-motor or the force exerted by the tag as it contacts the fur. Preliminary experiments with 10 breeds of domestic dogs *Canis lupus familiaris* during a total of 88 passes through the Japanese Gate showed that 8 breeds consistently passed with no discernible reaction to being tagged (using a powered deployment) while the remaining two breeds had no discernible reaction for 94% and 83% of passes but had a mild ‘reaction’ [either a pause of < 1 s, flinching or minor change in speed] for 6% and 13% of passes, and one of these breeds showed a ‘strong’ response [an extended pause, a change in trajectory, severe flinching, squatting or a radical change in speed] during 3% of passes.

Opportunistic bur-tag deployments on a variety of captive animals (with size ranges from Capybaras to Bactrian Camels *Camelus bactrianus*) showed reactions ranging from no discernible reaction to mild responses, although misplaced tag drops, for example onto the head, produced a ‘strong’ response and subsequent apparent anxiety to the burTS (Supplementary Film 8). Although the behaviour of animals in human care cannot represent that of wild animals, this work did serve to illustrate the interspecific variation and, importantly, demonstrated that any reaction to tagging by social species invoked an immediate apparent anxiety in adjacent individuals. This pattern was also clear in wild animals (Supplementary Film 9). Given this, exhaustive consideration of how various captive species might react to being tagged by a burTS is of limited value to those wishing to tag wild animals. Rather, in aspiring to promote a tagging process that ensures the maximum wellbeing of the study animals, we suggest that researchers wishing to use burTS on wild animals be mindful of anything that might affect how animals react to the tagging process. This includes how these are expected to vary according to situation (urban foxes, for example, may be more wary than non-urban animals) and how these change with changing neophobia to the burTS anyway (Fig. 3). Careful camera trapping documentation of reactions (see above) will be an important part of this.

### Potential difficulties

#### *Tag recovery*

This work neither looks at on-animal tag duration nor how tags, or their data, might be recovered. Some tags may download their data to a base station periodically *via* bluetooth or VHF, which is convenient but is limited in range (*51*) although larger tags might transmit data to satellites (*52*). Where the tags have to be recovered to access the data, tag recovery from shed bur-tags may be simpler than recapturing the animal although automatic tag drop-offs in collar-mounted tags are becoming more common (*53*). However, a homing beacon system, such as a VHF transmitter, is needed to find shed tags. This naturally increases the size and mass of the tag, which increases the likelihood of it being shed. As with all cases in this bur-tagging approach, the viability of the system will vary across target species.

### *Tag ingestion*

Tags that can be removed by the study animals have potential to be ingested. Although we did not observe any attempt to do this in any of our trials (including those with domestic dogs), the possibility should be considered. We suggest two possible approaches, one that the tags be coated with something that is unpalatable for the species concerned (*54*), and the other is that tags be made so that, should they be ingested, they would pass through the digestive system without harm. In this latter case, the tags need to be small enough to do this as well as strong enough to resist being broken up during mastication, if it occurs.

## Conclusions

In attempts to maximize animal welfare, we suggest that researchers working with tags on free-living species at least consider a bur-tagging approach. Importantly, a well-executed bur-tagged animal may be no more stressed by the process than it would be by being beset by natural burs so that even short deployments can be beneficial and facilitate the ethics of tagging (*55*). Animal tags are becoming increasingly miniaturized (*56*) so this, coupled with minimal adhesion mechanisms, which will presumably reduce the impact of the whole tagging system on the animal carriers (*13*), should make the case for bur-tagging more compelling with time. Indeed, as tags also become smaller and cheaper, there may even be a case for multiple tags to be deployed on the same individual, rather like vegetation burs (*57*). Our burTS only dispenses single tags from an immobile unit, using a primitive sensor system to detect animal type and position. However, with the accelerating use of AI, we believe that the future may allow burTS to deploy tags serially while recognising animal species, and perhaps even sex, also directing the barrel of the tag dispenser to provide the best tag placement.

Our study is highly preliminary, but we hope that it serves to highlight both the potential of bur-tagging for studies on wild animals as well as that many decisions need to be taken when bur-tagging systems are designed for particular species. These range from the sensors used and the manner by which the tag is to be deployed, to the specifics of the adhesion used between tag and animal. Careful camera documentation of animal reaction to burTS and the actual tagging process should help the community here.

Finally, we would like to think that this pilot work will serve to catalyse people to consider bur-tagging as an option for their study species and that, as it develops, the future will see both an improvement in tagged wild animal welfare and better data as a result.

# Declarations

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### Authors' contributions

RPW and US conceived and oversaw the work. JR constructed the BurTS with help from MDH. Fieldwork and work with captive and wild animals were conducted and/or aided by VC, JR, VS, MJ, HE, OS, KB, ED, FQ, AF, and JL. Laboratory work was conducted by JR, OS, KB and ED. RG and DMS advised on analysis undertaken by JR and RPW. RPW prepared the manuscript, with input from all other authors.

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### Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

### Ethics approval and consent to participate

The animal research was performed under the following ethics codes; SU-Ethics-Student-160322/4979, SU-Ethics-Staff-200123/582, SU-Ethics-Staff-110422/461.

### Consent for publication

Not applicable.

### Competing interests

The authors declare no conflict of interest

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# Figures

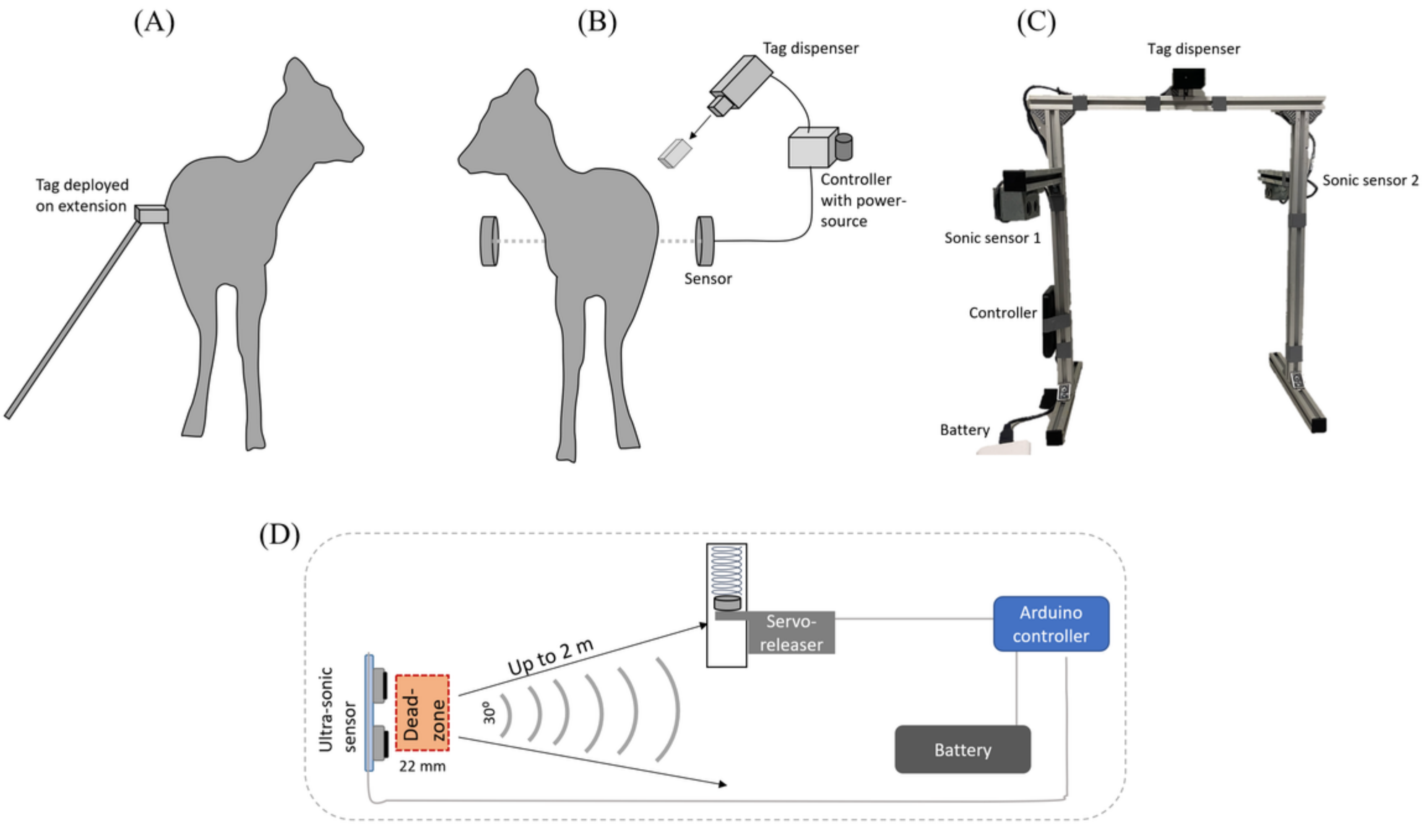
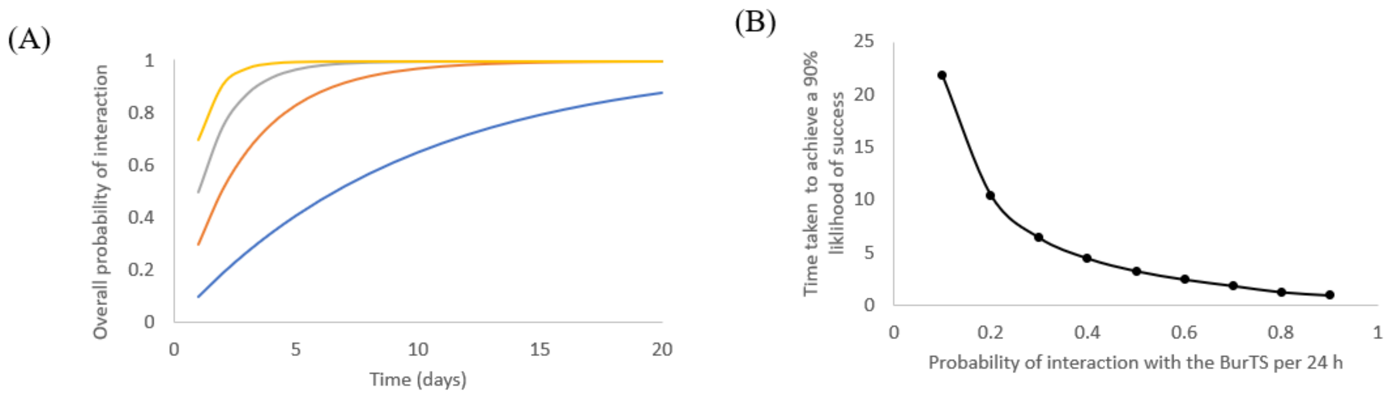


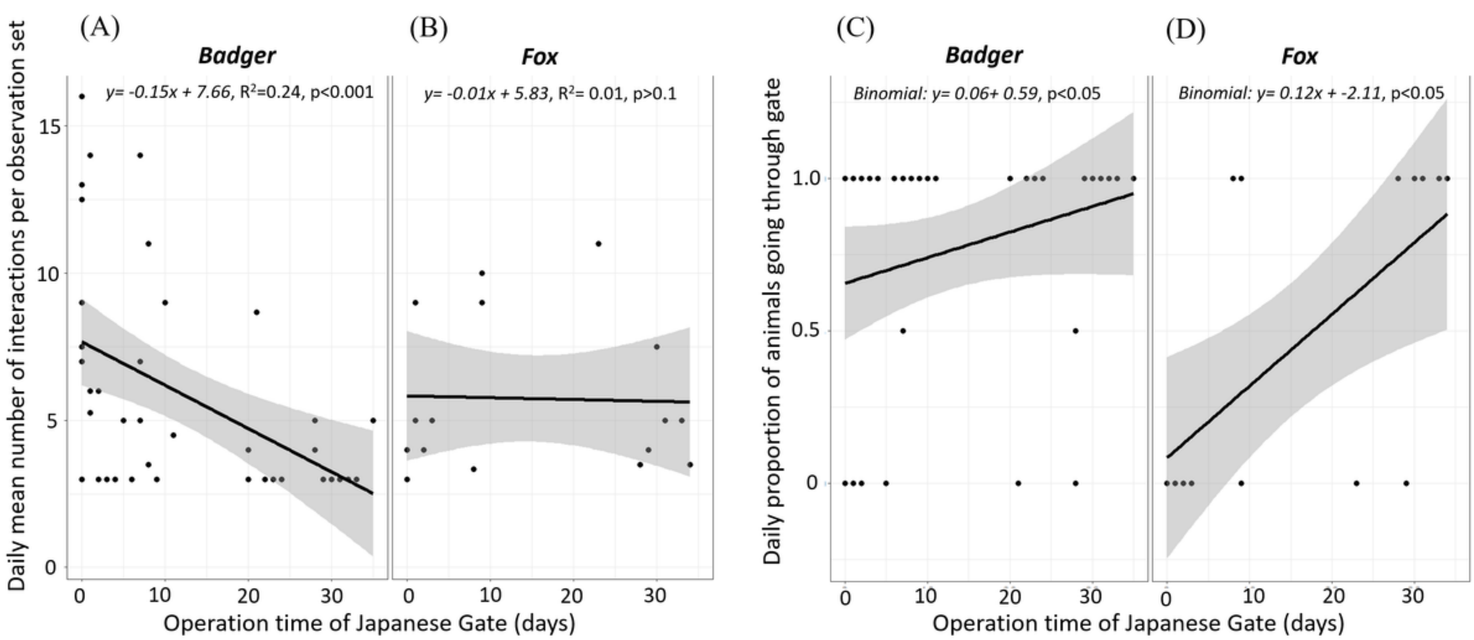

**Figure 1**

Schematic diagram of a bur-tagging system showing two basic types; (A) the most simple approach has the tag maintained at the end of a projection so that, when the target animal brushes against it, the tag is released and then sticks to the animal. In (B), a sensor unit informs a controller that an animal is in the appropriate place whereupon a tag dispenser projects the tag onto the animal. (C) shows the BurTS in place associated with one configuration - the Japanese Gate (JG 1) (see Supplementary Information 1 and 2). (D) Schematic design of the specifics of the BurTS in our principal Japanese Gate module (see Supplementary Information 1-3 for more detail).



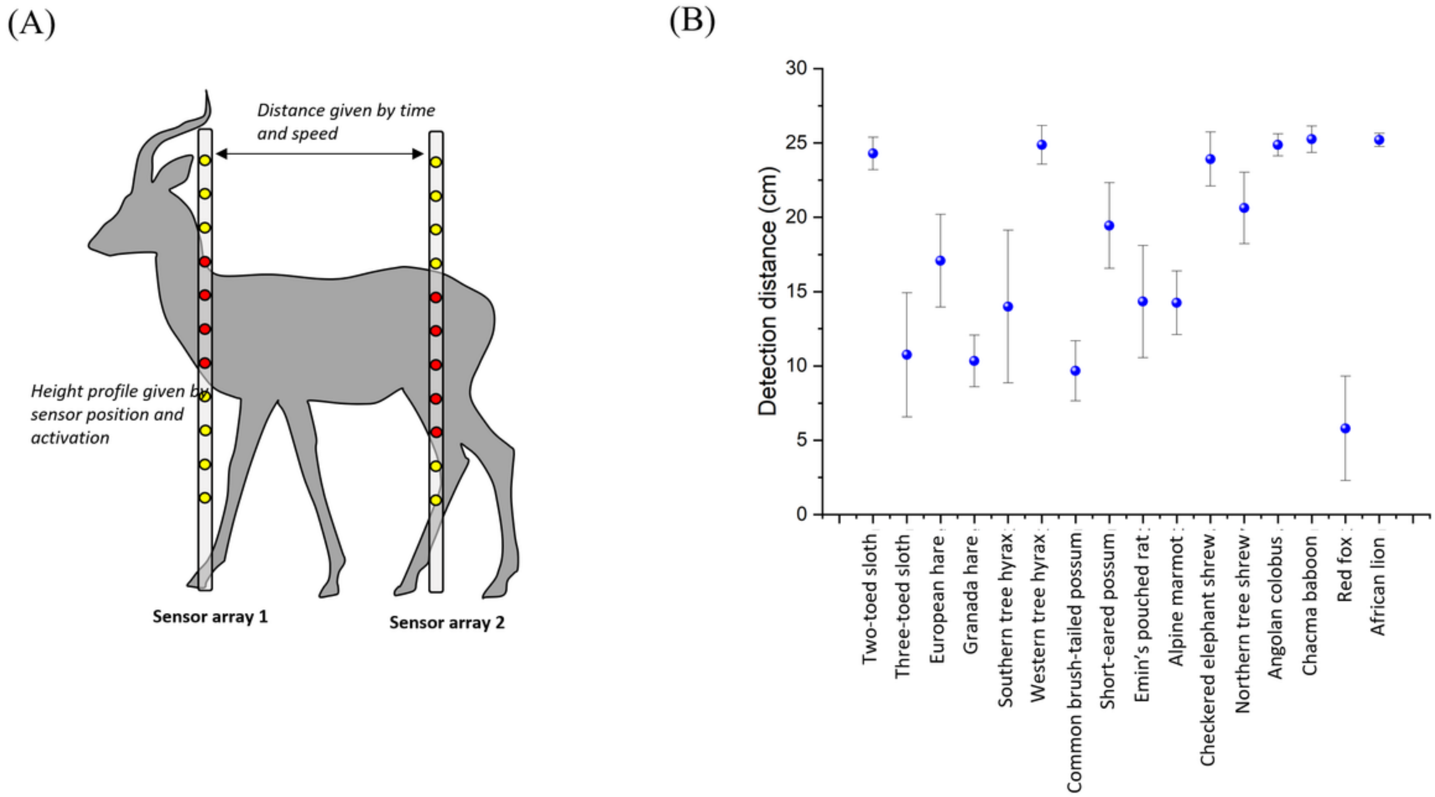

## Figure 2

(A) Changing overall probabilities of at least one successful tagging as a function of time according to various daily probabilities of having a target animal move into the BurTS operational area ($P_s$ - see eqn 1). These daily probabilities are indicated by the differently coloured lines (Blue = 0.1, Orange = 0.3, Grey = 0.5 and Yellow = 0.7 per 24 h period). (B) illustrates the time taken for there to be a 90% chance that at least one individual of the target species will be tagged as a function of the probability that an animal would move into the BurTS operational area over 24h. Note the non-linearity of this relationship.




## Figure 3

The total number of interactions (both attraction and repulsion) between animals and the Japanese Gate for (A) European badgers (B) Red foxes over deployment time and the proportion of animals that move through the Gates for (C) badgers and (D) foxes over deployment time.




## Figure 4

(A) Schematic diagram of how multiple (ultrasound) sensors in two arrays could help code for a target species. Here, the sensors (depicted by the circles) either 'see' the animal (red circles) or do not (yellow circles). The time-based sensor configuration 'seeing' the animal within both arrays can be used to help discriminate between species. (B) Variation in the distance at which an ultrasound sensor, set to be triggered at a distance of 25 cm, actually triggers according to species (species were represented by pelts and tested in the mid-line of the back between the shoulder blades - each point represents a grand mean consisting of 4 measurements per individual across 5 individuals per species – error bars are SD). Latin names for the various species are given in Supplementary Information 6.

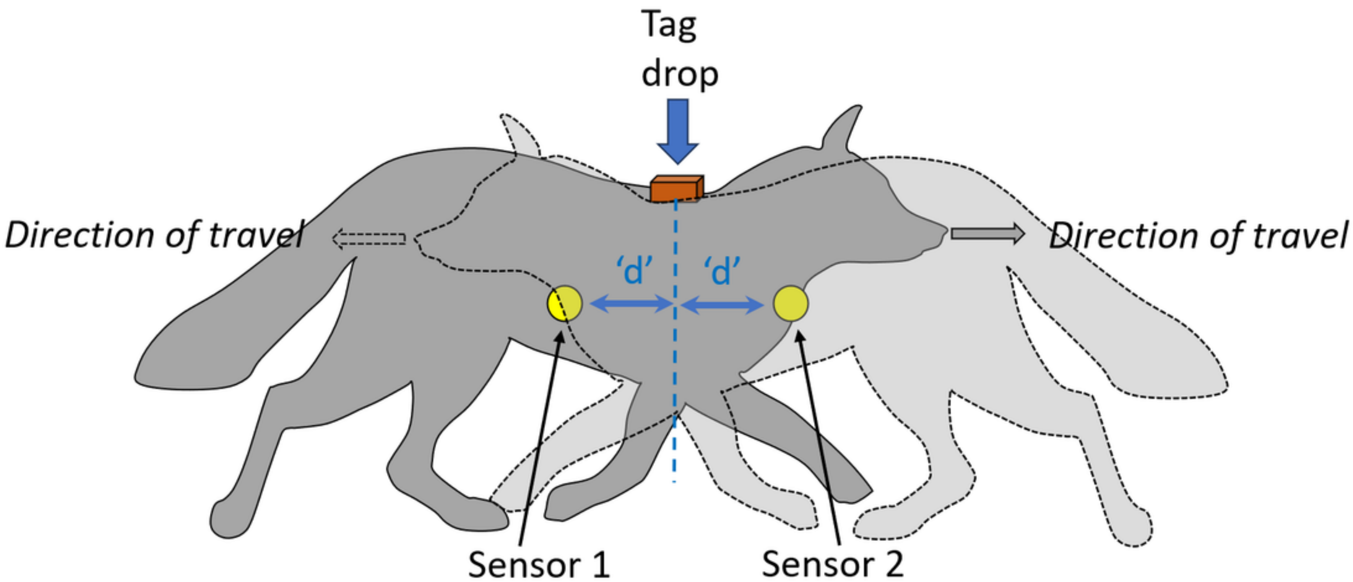
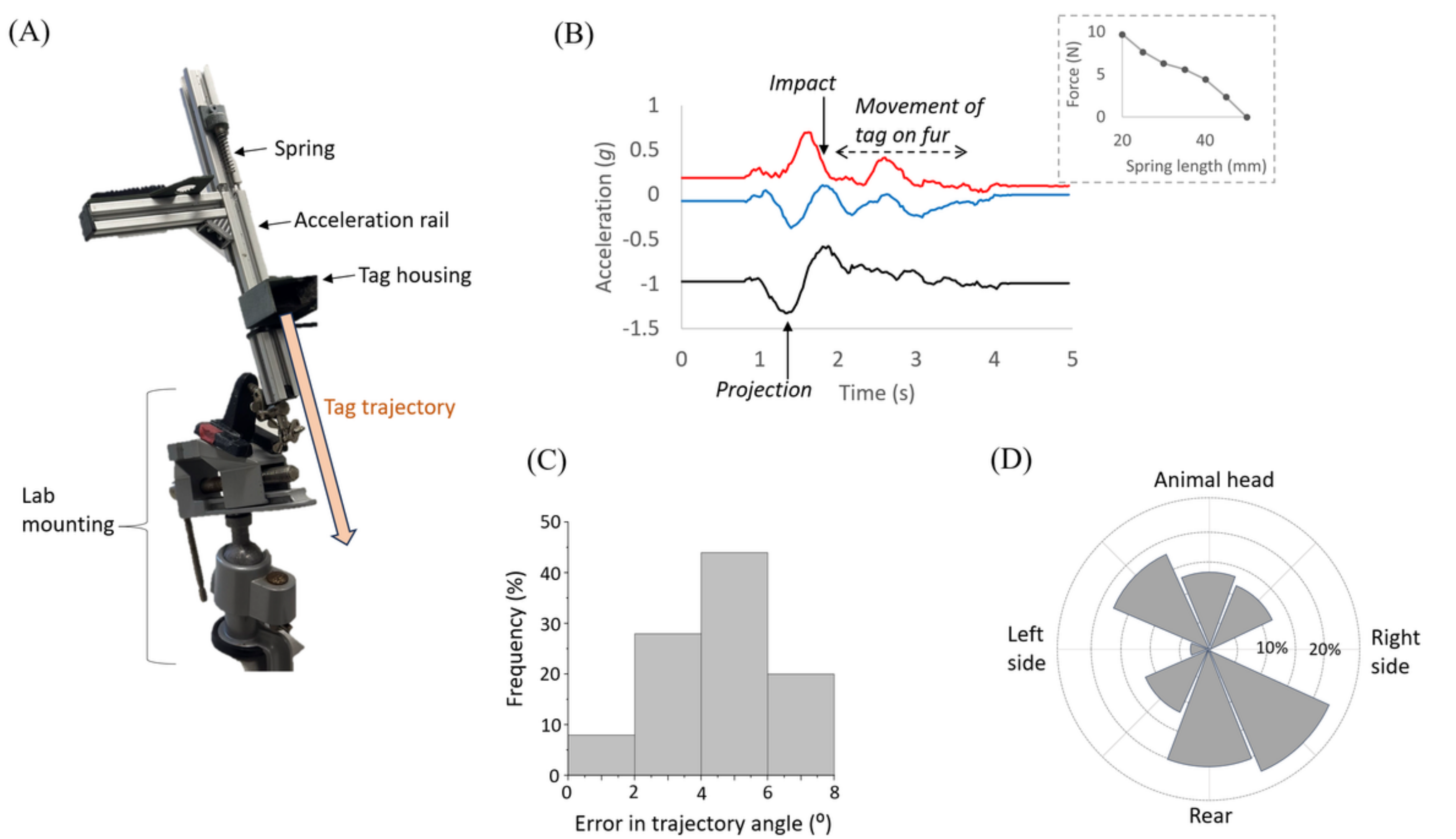


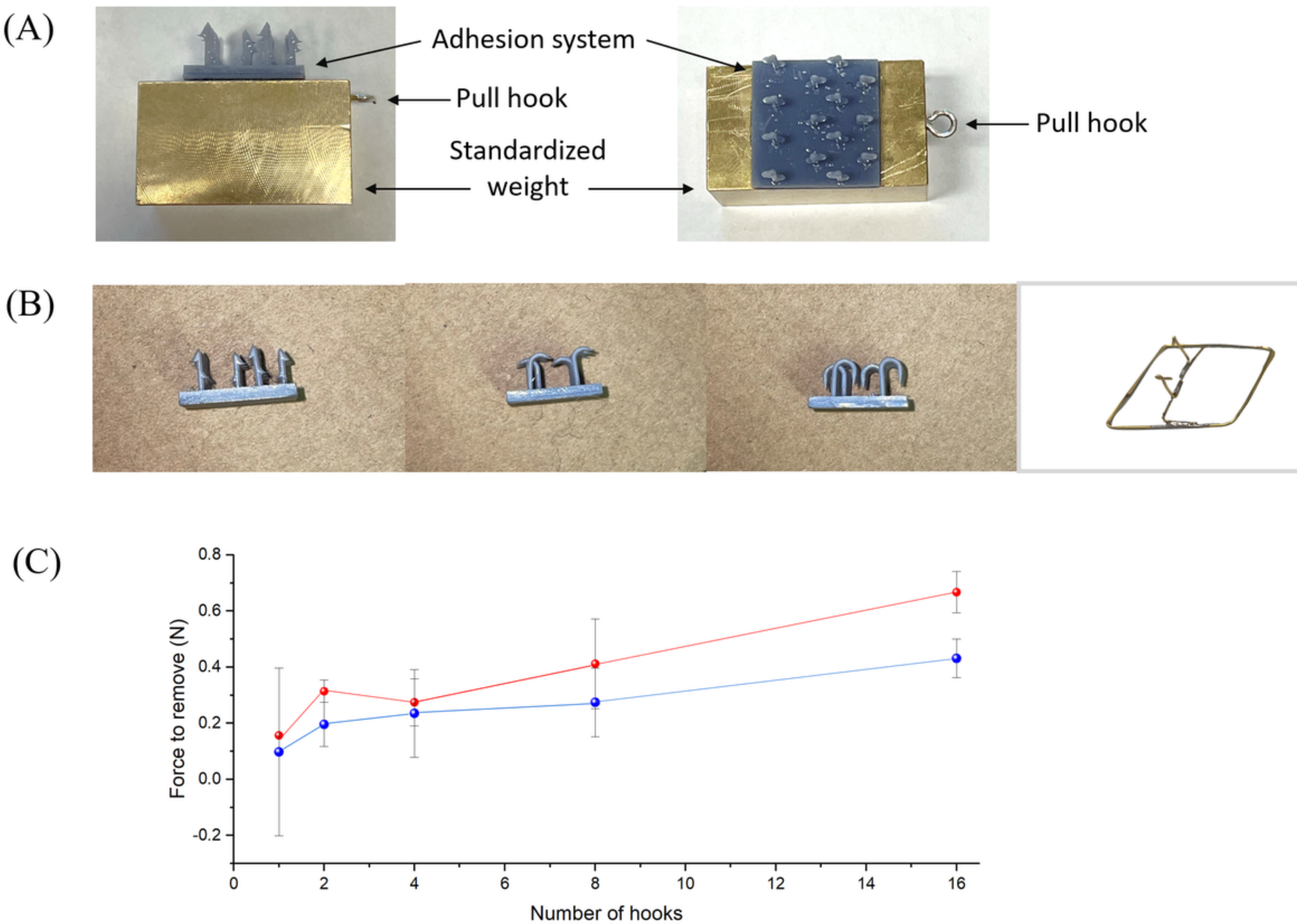

**Figure 5**

(A) Schematic diagram of a BurTS setup illustrating a system that allows for bi-directionality of the study animal. The two sensors (yellow circles) should be equidistant from the ideal tag spot and that distance should be equal to the distance between the first point that the animal triggers one of the sensors and the ideal tagging position.



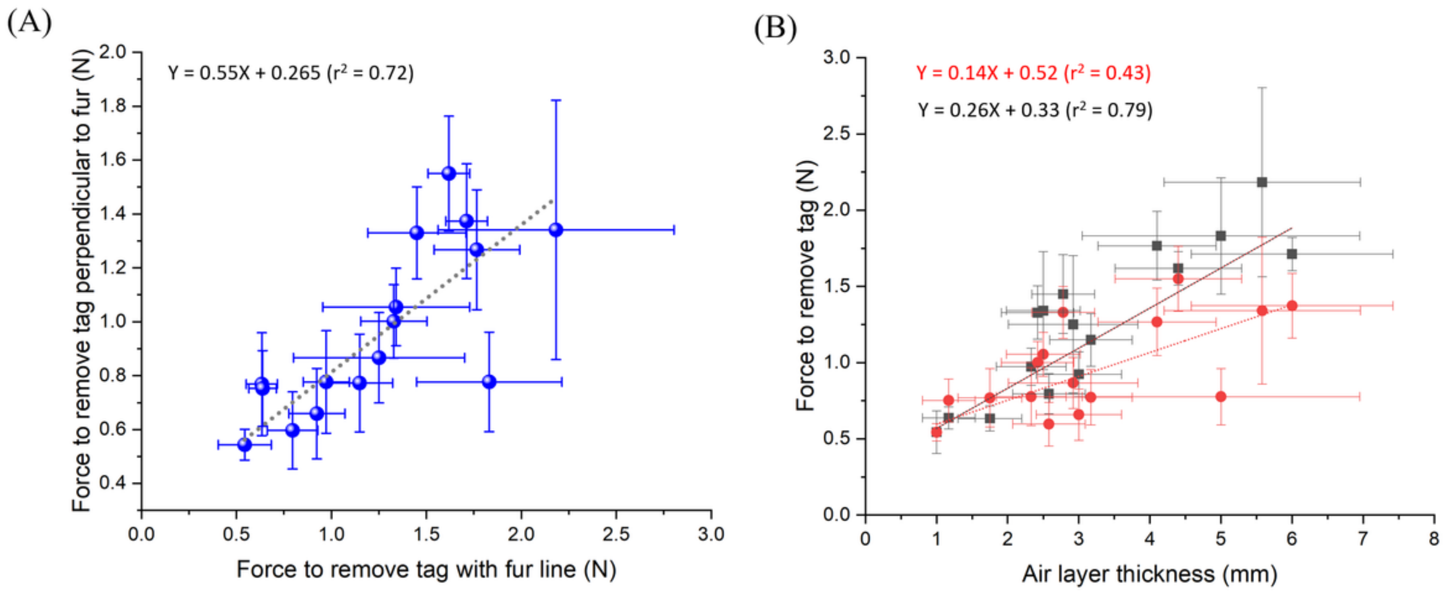
## Figure 6

(A) Compression spring-based tag dispenser illustrating how an acceleration rail can be used to constrain the trajectory of a tag exiting from a bespoke housing. (B) Triaxial acceleration of a 7 g tag projected from the system shown in (A) over a distance of 1.46 m onto a Red Deer pelt. The inset shows the force as a function of the spring length which led to the tag being projected at 2.9 m/s. Note the instability of the tag on the fur on contact, which is relevant for adhesion (see section 2.6). (C) Frequency distribution of the error in trajectory angle for the above scenario [note that the mode is not zero] and (D) illustration of the uneven sector occupation in the landing sites of the tag.




## Figure 7

(A) Side and dorsal view of the apparatus used to measure the forces required to dislodge a nominal bur-tag from the fur of test species. (B) Three examples of 3-D printed (in resin) synthetic attachment mechanisms used to simulate the adhesive properties of natural vegetation burs, in the form of hooks or barbs as well as an example (far right) where hooks were constructed out of brass by hand. (C) Example of the relationship between the force required to remove a given adhesive pad (the hand-made hooks shown in (B) above right - with an application force of 3.72 N) from a standardized animal fur (Red deer), pulling in the direction of the fur (red points and lines) and pulling perpendicular to the fur (blue points and lines), and the density of adhesive structures on the pad. Error bars are SE.




## Figure 8

(A) Relationship between the forces required to dislodge a standardized adhesive pad (see Fig. 7A) by pulling in one direction (with the direction of the fur) with respect to the forces required to remove it by pulling in another direction (perpendicular to the fur direction) for 16 different mammal species (see Fig. 4B for list - each point represents the grand mean of 4 measurements made from 5 individuals per species). (B) Relationship between the forces required to dislodge the standardized adhesive pad (Fig. 7A) and species fur thickness (assessed using a 'featherometer' applying a perpendicular pressure of 0.5 $N/cm^2$) for pull directions 'with the fur' (black squares) and 'perpendicular to the fur' (red circles) for 16 different mammal species. Error bars are SD.

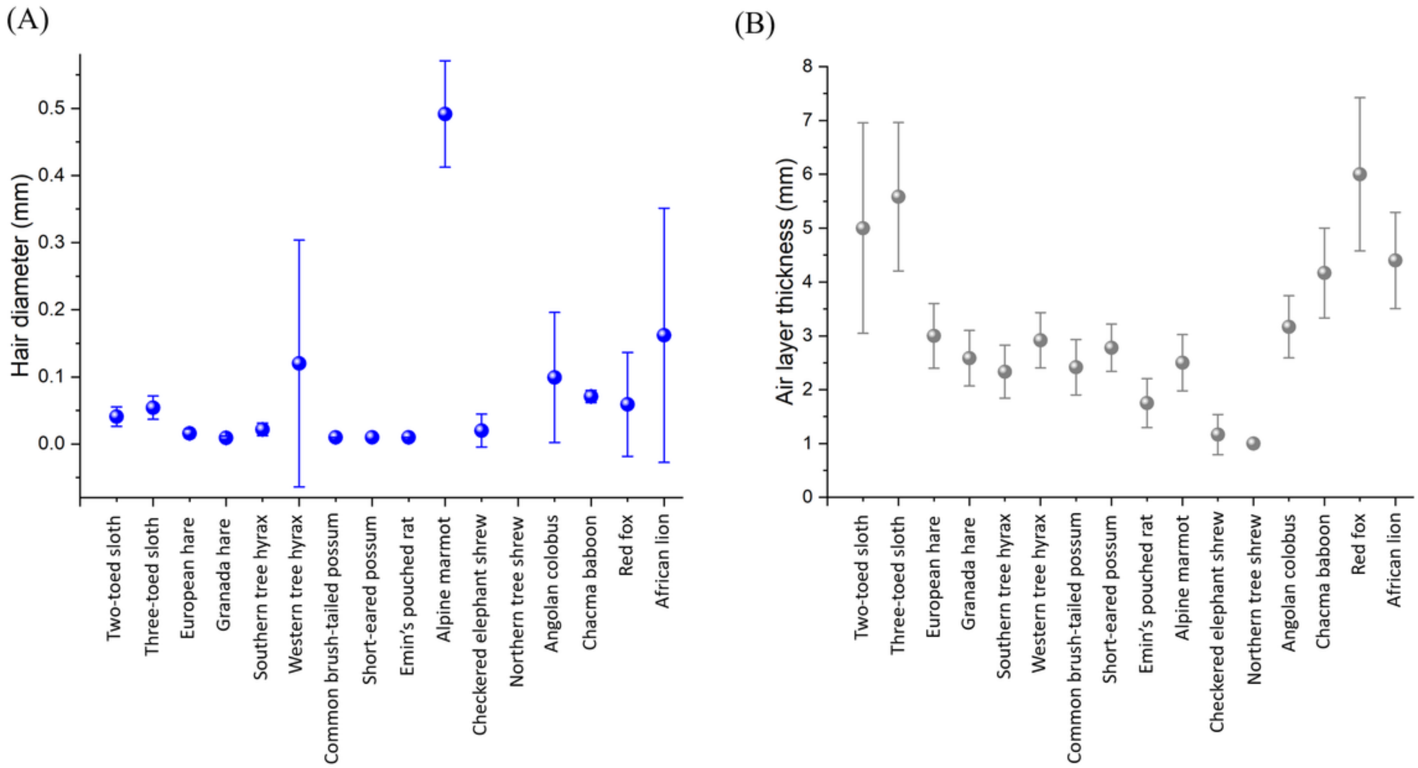



**Figure 9**

Inter-specific variation in (A) fur hair diameter (taken at a point halfway along the hair) and (B) air layer thickness for 16 species of mammal from 8 Orders [data taken from animal pelts and derived from measurements made in the dorsal mid-line of the back, between the shoulder blades – each point (± SD) is the grand mean from 4 measurements taken from each of 5 individuals.

# Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryInformation3.6AnimalBiotele.docx