Quantifying the effects of outdoor activities on ecological systems

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Summary

Sportive and recreational outdoor activities offer an opportunity to connect with nature and have a plethora of positive physiological and psychological effects on humans. At the same time, they can be detrimental to the respective natural environment. Hence, it is desirable to uphold the positive effects on humans, while minimising negative effects on the environment. The biggest challenge in achieving this is to identify the relevant factors involved. These need to be studied and quantified to derive knowledge-based management recommendations.

River ecosystems face an especially high recreation load: They are home to a variety of species but also provide opportunity for a range of outdoor activities. I investigated potential negative impacts of paddling activity on the reproduction of common kingfisher *Alcedo atthis* and river trout *Salmo trutta fario*. To do so, I quantified which properties of a human activity determine the activity's influence on common kingfishers' feeding behaviour. I find that fast-moving, lingering, or loud activities affect the birds more. I also studied the effect of paddle strokes and sedimentation on the larval development of river trout, finding no significant impact. Neither study finds clear evidence of a negative impact of moderate paddling activity. Due to the study designs, no statement on heavy paddling activity can be derived. However, even small disturbances can have a strong effect on an ecosystem. I show an example for this in a study on the progression of damage inflicted on the lichen cover of a pristine cliff site by bouldering activity.

Technological and societal changes in the context of digitalization open novel methods to quantify effects of outdoor sports on ecological systems. I made use of social media as a data source to study a shift in recreational cycling behaviour induced by epidemic control decisions at the onset of the COVID-19 pandemic. Being able to study changes in behaviour across the entirety of Germany, I quantified differences between urban and rural regions. In another study, I show the feasibility of video traps recording continuous footage while employing modern computer vision methods to reduce data analysis efforts. The setup used works fully off-the-grid, showing that video data is an interesting option in today's wildlife monitoring toolkit.

Zusammenfassung

Sportliche und der Erholung dienende Outdoor-Aktivitäten schaffen eine Verbundenheit zur Natur und haben eine Vielzahl an positiven physiologischen und psychologischen Effekten auf die Ausübenden. Gleichzeitig können sich diese Aktivitäten negativ auf die jeweiligen natürlichen Ausübungsorte auswirken. Es ist erstrebenswert die positiven Auswirkungen auf Menschen zu erlauben und gleichzeitig die negativen Auswirkungen auf die Umwelt zu minimieren. Die größte Herausforderung hierbei ist, die relevanten Faktoren zu identifizieren. Diese müssen erforscht und quantifiziert werden, um wissensbasierte Management-Empfehlungen abzuleiten.

Fluss-Ökosysteme sind von einem besonders hohen Erholungsdruck betroffen: Sie beherbergen eine Vielfalt an Spezies, bieten aber auch Gelegenheit für verschiedene Sport- und Erholungs-Aktivitäten. Hierzu erforschte ich potenziell negative Effekte von Paddel-Aktivität auf die Fortpflanzung des Eisvogels *Alcedo atthis* und der Bachforelle *Salmo trutta fario*. Dafür identifizierte ich welche Eigenschaften von menschlichen Aktivitäten das Fütterungsverhalten des Eisvogels maßgeblich beeinflussen. Ich stellte fest, dass schnelle, lange verweilende und laute Aktivitäten am ehesten eine Reaktion des Eisvogels verursachen. Weiterhin untersuchte ich auch den Effekt von Paddelschlag und Sedimentation auf die Larven-Entwicklung der Bachforelle – konnte hier aber keine nennenswerte Auswirkung nachweisen. Keine der beiden Studien erbringt klare Beweise für einen negativen Effekt von moderater Paddel-Aktivität. Aufgrund des Studien-Designs kann keine Aussage zu starker Paddel-Aktivität getroffen werden. Dementgegen können jedoch auch scheinbar kleine Eingriffe große Auswirkungen auf ein Ökosystem haben. Dies zeige ich in einer Studie zum Rückgang von Flechtenbewuchs bei einsetzender Kletter-Aktivität an einem vorher nicht bekletterten Fels.

Technologischer und gesellschaftlicher Wandel im Kontext von Digitalisierung eröffnet neuartige Methoden zur Quantifizierung der Auswirkungen von Outdoorsport auf ökologische Systeme. Ich nutzte soziale Medien als eine Datenquelle um die Veränderung im Radfahr-Verhalten zu untersuchen, welche durch Vorgaben zur Seuchenbekämpfung zu Beginn der COVID-19-Pandemie hervorgerufen wurde. Somit war ich in der Lage Verhaltensänderungen von Radfahrenden in ganz Deutschland zu untersuchen und konnte Unterschiede zwischen urbanen und ruralen Räumen quantifizieren. In einer anderen Studie

demonstriere ich die Macharkeit von kontinuierlich filmenden Videofallen, gekoppelt mit modernen Methoden der Computervision zur Reduzierung des Aufwands der Datenanalyse. Der hierfür benutzte Video-Aufbau ist vollkommen autark, was Videofallen zu einer interessanten Methode zur Wildtier-Erfassung macht.

Introduction

The effects of outdoor sports are multifaceted, with benefits for human physical and psychological well-being (Kahlmeier et al. 2017, Stott 2019, BMUV Members 2021, BMUV 2023) and developing awareness for nature conservation (Bell et al. 2007). At the same time, the potential detrimental effects on local ecosystems are not well studied. Consequently, it is of prime interest to understand sportive and recreational outdoor activities from an ecological and an administrative point of view (Carter et al. 2012, Zink et al. 2022). For this, quantifying the effects of outdoor sports on ecological systems is necessary. In this dissertation, I use emerging novel methods alongside established methods from the field of ecological research for this purpose.

The term sport is multifaceted and is described by the Council of Europe (1992) as "all forms of physical activity which, through casual or organised participation, aim at expressing or improving physical fitness and mental well-being, forming social relationships or obtaining results in competition at all levels". The term nature is an even more complex concept, lacking an agreed-upon definition (Ducarme & Couvet 2020). Nevertheless, nature is often defined as including living material reality, e.g. animals or plants, and inert material reality, e.g. rocks. Nature also includes all features, forces and processes that occur independently of people, e.g. the weather, mountains, reproduction or growth (Cambridge Dictionary 2024). Following that description, outdoor sports are comprised of nature-based sports carried out alfresco in corresponding natural settings (an ecosystem with all its processes and biodiversity intact), semi-natural settings (an ecosystem with most of its processes and biodiversity intact) or urban green spaces (open-space areas in an urban setting reserved for e.g. parks, gardens or canopy). In contrast to outdoor sports, outdoor recreation often has no competitive aspect and focuses on experiencing nature and stress reduction instead of physical activity (McCullough et al. 2021). The difference between outdoor sports and outdoor recreation is sometimes blurry, especially due to the trend of sportification (Arnegård & Aandell 2018). In Germany, 72% of the population aged over 15 are actively participating in some kind of sport, with 15 million people exercising via outdoor sports on a weekly basis (BMU Beirat 2020). Moreover, the economic sector of sports contributed 2.3% to the German GPD in 2018, making it a relevant economic factor (GWS 2021). Outdoor sports are not only of economic value, but also present an opportunity for social activities and individual development of self, with participants fostering their independence, spontaneity, individuality and self-realisation (Türk et al. 2004). Additionally, sportive and recreational activities in nature promote physical and mental well-being of participants (Kahlmeier et al. 2017, Stott 2019, BMUV Members 2021, BMUV 2023). Quality of life and general health are increased and movement associated health issues prevented (Stott 2019, BMUV Beirat 2020, Bundesumweltministerium 2021). For mental health, green environments are more beneficial than urban grey environments, meaning areas in urban settings without greenery (Fong et al 2017). Increased greenness is associated with stress reduction (Bowler et al. 2010), lower likelihood of psychological distress and other positive mental health outcomes, especially with physical activity as a mediator for stress reduction (Hartig et al. 2014, Engemann et. al. 2019).

Sportive and recreational outdoor activities enable participants to connect with nature, facilitating ecological understanding and awareness, and thus advocate nature conservation (Bell et al. 2007). Outdoor activities are often concentrated in areas with high ecological value (Türk et al. 2004). Due to transformation and homogenisation of the landscape, induced by agricultural practices and population growth, natural habitats are already under pressure (Ramankutty et al. 2018, United Nations et al. 2019, Ellis et al. 2021). According to IPBES (2019), 75% of the earth’s surface has been changed through anthropological development, 95% of wetland are lost and 25% of all known plant and wildlife species are endangered. Therefore, it is of prime interest whether and to which degree outdoor activities increase pressure on species or habitats.

When aiming to measure the value of ecosystem services, a number of methods with varying scopes are available. Qualitative studies have shown that participants recognize the enormous value of ecosystem services, but find it difficult to describe the benefit, let alone measure it (Stålhammar & Pedersen 2017). Today’s default is to measure such services with monetary values, which is reasonable to some degree: a sum of money is fathomable and can describe the importance of things. It attempts to put into perspective the costs of neglegted ecosystems and can lead to the development of guidelines and to newly protected areas (Milcu et al. 2013). The Travel Cost Method (TCM) surveys preferences and sets them into relation to trips made and their respective costs (Brown & Mendelsohn 1984, Smith & Kaoru 1990). The Contingent Behaviour Method (CBM) estimates changes in human well-being and ascribes value to them (Filippini et al. 2018). The Common International Classification of Ecosystem Services (CICES) makes by far the most detailed measure of value, by classifying services and addressing them in the context of human needs (Haines-Young & Potschin 2012). Ecosystem services are classified as a providing, regulating or cultural service, with outdoor sport being part of the latter (Kulczyk et al. 2018). However, critics emphasise that ecosystem services are de facto priceless, as they cannot be bought or replaced with money. This means the actual value is most likely underestimated, when using only the proxy of monetary value (Haines-Young & Potschin 2012).

Ecosystems are key to sustaining life and provide valuable services, such as biomass production, regulation of climate, erosion prevention or water filtration (Millenium Ecosystem Assessment 2005). Research suggests we are currently headed towards an ecological crisis due to massive loss of biodiversity and habitats (Pimm et al. 2014, Ceballos et al. 2015, De Vos et al. 2015). This de-stabilizes species communities, thereby threatening the ecosystem’s ability to provide its services. This crisis seems to be induced by humanity (Barnosky et al. 2011, Raven et al. 2011, Rosenberg et al. 2019, Cowie et al. 2022), e.g. via agriculture (Ruddiman 2003, Pimm et al. 2014), habitat destruction (Vitousek et al. 1997, Teyssèdre & Couvet 2007, Behutiye et al. 2020), climate change (Urban 2015) and other factors like sealing of soil, hunting, pollution, neobiota and transmission of diseases (Harvell et al. 2019). As we face immense loss of biodiversity and the risk of destabilizing valuable ecosystems, it is of paramount importance to act responsibly and with foresight in all activities and decisions concerning the environment. Studying the interactions between humans and their surrounding ecosystem is a multifaceted field, since both, ecosystems and the ways humans interact with them, can vary widely. Wohlgemuth et al. (2019) provide a comprehensive overview of disturbance ecology concerning the impact humans can have on plants and plant communities. The approach in this thesis to interactions between human outdoor recreation and ecosystems focuses mostly on animal species.

The effects outdoor activities have on nature are diverse and are expected to expand and increase (Larson et al. 2016, Olson et al. 2018). Sportive and recreational outdoor activities may be more environmentally friendly than consumptive activities, such as resource extraction. Still, outdoor activities can have negative effects on nature (Larson et al. 2016), with e.g. recreational activities being listed as a threat to 188 bird species globally (Steven &

Castley 2013). Outdoor activities can lead to habitat degradation or habitat loss, and can induce a variety of responses or changes in animals (Tablado & Jenni 2017). Initially, individuals are affected, which can display behavioural or physiological changes, e.g. flight initiation and vigilance (Mainini et al. 1993, Naylor et al. 2009) or exposure to stress (Müllner et al. 2004, Arlettaz et al. 2007, Braunisch et al. 2011). If these effects on individuals are strong enough, they can lead to changes in survival, e.g. changes in reproductive success (Beale & Monaghan 2005, Finney 2005), in foraging and feeding behaviour (Frid & Dill 2003) or in spatial or temporal habitat use (George & Crooks 2006, Rogalda e al. 2011). Finally, if a sufficient number of individuals is affected, changes in population trends or distribution can emerge, e.g. changes in abundance (Banks & Bryant 2007, Heil et al. 2007, Reed & Merenlender 2008) or regional species composition (Riffell et al. 1996, Kangas et al. 2010). These numerous possible effects can affect a wide variety of species and habitats – and in turn, an affected species can influence its community with its responses and changes. Additionally, when tourism expands into new regions, it may add pressure on habitats already under stress caused by climate change (Balmford et al. 2015) or other factors. Furthermore, each sportive and recreational outdoor activity is different and can have different effects on nature (Hennig & Künzl 2012). Since there is a large variety of possible interactions of outdoor sports and nature to be studied, reliable but streamlined methods are needed to improve time and resource efficiency. For this, a combination of established ecological methods and novel methods can be useful.

Due to diverging individual values or activity aims, and sometimes due to research gaps, conflicts around outdoor activities can arise on an egocentric, ecocentric or anthropocentric level. Involved parties can be nature conservationists, sportspeople of the same or a different activity, residents etc. Conflicts are categorized as follows: Interpersonal conflict (Jacob & Schreyer 1980) arises when there is activity goal interference due to other recreationists or sportspeople's behaviour. Social value conflict (Vaske et al. 1995, Vittersø et al. 2004) occurs when a person suspects the existence of a problem caused by other users or their activity. The person does not necessarily observe or experience suspected problem directly. Lastly, environmental values conflict arises when a person's perception of other visitors' general behaviour or specific outdoor activity does not comply with their own personal environmental values (Floyd et al. 1997, Noe et al. 1997, Manfredo et al. 2004, Rossi et al. 2015).

It is worthwhile to examine conflicts around outdoor recreation, since they can indicate an underlying nature conservation issue. Recreationists tend to have an enhanced awareness for nature (Calogiuri & Elliott 2017) and their collective experience can provide valuable insights. Conflicts around outdoor activities are often about disturbing or endangering plant or animal species by disrupting activities or developmental processes. In addition to predators and environmental incidents, human activity can induce disturbances (Reichholf 2001, Wohlgemuth et al. 2019). In general, disturbances may lead to different outcomes, which are categorized as follows: 1. physiological effects (increased heart rate and energy expenditure), 2. behavioural effects (increased vigilance, movement response) and 3. ecological effects (distribution, demographic changes due to avoidance of areas) (Reichholf 2001, Gill 2007, Bötsch et al. 2017, Wohlgemuth et al. 2019). On top of this, a disturbance may also affect species on community and population level (Pinek et al. 2020, Schafft et al. 2021). A particular kind of disturbance by outdoor activities are human-wildlife interactions, meaning interactions between humans and animals. Such interactions are virtually unavoidable and will happen more often in the future due to climate change and shrinking natural habitats (Nyhus 2016). Human-wildlife interactions can be passive (e.g. objects left behind by visitors) or active (e.g. feeding wildlife), with positive, neutral or negative outcomes. Negative interactions, for example when humans get hurt, are often framed as human–wildlife conflict (Bhatia et al. 2018). Tablado & Jenni (2017) present a hierarchical model of the impact of human recreation on animals, distinguishing four levels of interaction between humans and animals, starting with detection and ending with changes in population trends and distribution. They argue that a disturbance must progress through these levels in order, meaning if a disturbance does not affect the individual's behaviour, no effect on the population as a whole can arise. Additionally, they give a wide range of possible factors that can affect the human-wildlife interaction at each stage, some of which I observe in the studies presented in this dissertation.

A good example to illustrate the intricacies of conflicts in outdoor sports is paddling activity, such as kayaking, stand-up paddling or canoeing. These conflicts are of particular interest here, as several manuscripts in this thesis examine related issues. In the context of paddling activity, conflicts can arise between paddlers, fishers and nature conservation. The latter parties might be concerned about negative effects on local fauna, for example by scaring breeding or foraging birds and fish away (Zauner & Ratschan 2004). Other concerns are direct mechanical effects on fish like injuries, destruction of spawn, increased sedimentation or turbidity. Paddling effects are suspected to lead to behavioural changes of fish such as swarm coherence and activity phases. This would increase the risk of predation, while food availability decreases (Zauner and Ratschan 2004). Similarly, effects on dragonfly larvae can be critical, as sediment swirls get into the larvas' gills and impair their respiratory system. Turbidity may lead to developmental disorders and may drift the larvae off into untypical habitats (Schorr 2000). Additionally, boats may spread invasive species (Stasko et al. 2012). Even human presence by itself, e.g. while performing outdoor sports, can disturb wildlife, change animal behaviour and may affect the animal's metabolic system (Reichholf 2001). In the vicinity of kayaking, swans show increased locomotion and less foraging activity, resulting in a 34% higher energy expenditure which affects their general level of fitness (Clausen et al. 2020). Despite these findings, the effect of recreational activities varies depending on species and location, and it is difficult to elucidate the full extent of effects induced by any given outdoor activity (Batten 1977, Klein et al. 1995, Laursen et al. 2005, Alexandrino et al. 2016, Naidoo & Burton 2020). Although there seldom is proof for these hypothetical paddling impacts or knowledge of the impacts' scale (Zauner & Ratschan 2004), decreased reproduction rates of fish are often blamed on paddling.

For every outdoor activity, there is a plethora of possible effects on local ecosystems. This yields a large number of ecological questions that require answering to reconcile nature conservation and outdoor activity. These answers help understand whether an outdoor activity affects indivuals or the population as a whole, and uncover the crucial factors that drive the impact. These factors determine to which degree management measures are required and appropriate. Understanding them is necessary for knowledge-based management aiming to conserve nature while retaining the positive effects of outdoor activities on humans. This can be achieved with a scientific study that establishes if, how and at what level human activity affects a species or ecosystem (Tablado & Jenni 2017). In this thesis, I use both traditional and novel methods to conduct such studies.

Synopsis

Quantifying the effects of outdoor sports on ecological systems is relevant from multiple angles. From a nature conservation point of view, it is important to study the manner and the gravity of the impact these activities have on ecosystems and conservation aims. The goal of such a study is to identify at what point there is a relevant impact on the respective ecosystems that threaten their stability, and at what point the impact is minimal (Tablado & Jenni 2017). Such insights make it possible to derive suitable management recommendations that are fit to protect the respective ecosystems, their key services and species, while allowing for outdoor recreation and sports to take place and for people to enjoy the benefits of such activities. Furthermore, there is a societal point of view to consider. Any given landscape has interest groups, e.g. land owners, local residents or visitors. Additionally, most landscapes provide a fitting setting for multiple sportive or recreational activities. This variety of interests provides an enormous potential for conflict (Noe et al. 1997, Floyd et al. 1997, Vaske et al. 1995, Manfredo et al. 2004, Vittersø et al. 2004, Rossi et al. 2015). Such conflicts are not always of interpersonal character, but can also involve nature conservation concerns. Pacifying these conflicts requires a sound scientific understanding, to find and implement appropriate managements measures. However, the necessary scientific understanding is not always established at the required level of detail to solve the respective conflict. This sometimes leads to the implementation of management measures based on personal experience, anecdotal evidence or other forms of reasoning. These measures can be somewhat successful, but are unlikely to address the underlying ecological framework pointedly and sustainably. Instead, when the scientific understanding is lacking, an ecological study should be conducted to discover missing facts and thus aid in creating a goal-oriented solution.

There are many established methods available to conduct an ecological study. The most labour-intensive step is oftentimes data collection and refinement. Here, trained experts need to spend a significant amount of time gathering raw data or reviewing data points. For example, for the observational study in manuscript 2 “The influence of recreational activities on temporal feeding patterns of the common kingfisher (*Alcedo atthis*)”, research assistants spent a total of 213 hours in the field over the span of 25 days, observing common kingfisher nests at four different locations. There are emerging technologies and data sources that can reduce this manual effort, among them artificial intelligence (AI) and novel data sources, such as social media. With the usage of AI it is possible to automate tasks that otherwise would require trained experts to invest time and effort, e.g. reviewing camera trap footage (Beery et al. 2019). Novel data sources make use of already present information, which was not originally gathered for the respective study. Geo-tagged data (Schwartz & Hochmann 2014, Hamstead et al. 2018) or sentiment analysis of social media posts (Ronan 2013, Roberts et al. 2018, Alaei et al. 2019) can yield relevant ecological insights. This thesis uses both established and novel methods of data gathering and analysis to gain quantitative insights into ecological questions in the context of outdoor sports.

Due to recreationists' enhanced awareness for nature and conservation issues, conflicts around outdoor sports are useful indicators for negative impacts on ecosystems (Calogiuri & Elliott 2017). Parties involved in these conflicts each have particular interests at heart, which is not always nature conservation per se. When a nature conversation issue is brought up in such a conflict, the argument needs to be vetted thoroughly. If the concern is substantial, conducting a literature survey is in order. Transferring insights from the literature to a different context can be difficult (Buma 2021): On the one hand, ecosystems are subject to a variety of localized pressures, e.g. adjacent land uses. On the other hand, outdoor activities can exert pressure on an ecosystem in a number of ways. Still, the growing body of work in sports ecology is a valuable resource to evaluate conflicts from a scientific point of view. If a literature survey does not yield a sound factual basis that provides a suggestion on how to resolve to conflict, a new study is called for. The results of this study then provide a neutral and fact-based assessment of the ecological issue that lies beneath arguments made in the conflict. In general, every sportive outdoor activity has an effect on nature – the central question is which effects have a lasting negative impact on nature and how to circumvent these.

In the following paragraphs, the five manuscripts included in this thesis will be described with a focus on the methodology used and, where applicable, the conflict that the study draws on. Most of the manuscripts share a common topic: The effect of paddling activity on river ecosystems. Despite studying other topics, the remaining manuscripts complete the picture in terms of established and novel methods to quantify effects of sport activities on ecosystems. Taken together, this body of work allows some insight into the potential and current trade-offs of novel methods, in contrast with the more established ones. Kindly note that this dissertation consists of five manuskripts, which I collaborated on with colleagues. A detailed break-down of my specific contributions to each manuscript can be found in the paragraph “List of manuscripts included in this dissertation & declarations of contributions”. For brevity, in the body of this dissertation first person singular is used throughout.

“Outdoor cycling activity affected by COVID-19 related epidemic-control-decisions” is the first manuscript presented. In it, I study the change in human behaviour effected by restrictions imposed in Germany to control the spread of COVID-19. Using cycling as a proxy for sportive outdoor behaviour, I investigated differences between urban, rural and conserved areas as indoor sports were being restricted. This study is the first to use fitness and outdoor apps to quantify the volume of sportive cycling traffic. In particular, I use the activity on Strava high-score boards to measure changes in traffic on particular path segments. Using data that was not gathered for the purpose of a specific study always requires great care in its interpretation. In this instance, the year-over-year growth of activity on the high-score boards is linked to the growth of the platform, not an increase in cycling activity in Germany. Removing the year-over-year growth from the data was a key step enabling our analysis. Additionally, besides sportive cycling traffic, the enacted epidemic control decisions caused a shift in commuting behaviour as well. Disentangling these two motivations behind increased cycling activity is a key challenge in the study. I meet this challenge by carefully defining criteria for path segments to be eligible. Notably, I exclude segments that have a large variation in the mean count of attempts per user, which would indicate that the segment is part of a popular route for commuters, and not predominantly used by recreationists. The study shows that while epidemic control decisions lead to an increase in sportive outdoor cycling traffic in urban green spaces, such an increase is not observed in rural areas.

Traditional methods would gather visitor count data on-site, e.g. counting cyclists in person or installing inductive counters (e.g. Wolf et al. 2012). Using social media data for this study made it possible to gather data remotely via the internet. This allowed the study to look at sites all across Germany, without having to organize a concerted effort at all sites, which would have been well outside the scope of the project. This advantage has to be weighed up somewhat against potential biases in the data, which can originate from a multitude of sources, e.g. from gender or age imbalances between recreational cyclists overall and users of the social media platform used as a source. In addition, the study required a careful data selection method. In particular, I was interested in recreational cycling and needed to exclude commuters from the data. Finding and validating appropriate selection criteria is not trivial, and as of yet there is no extensive body of work to find guidance in. Finally, it would have been a complex task to combine data from multiple platforms, since they do not use standardized categories. As an example, another fitness app could define path segments or criteria for publication on the high-score boards differently. However, even with these considerations, the study provides useful insights.

There is further potential to make utilization of social media or other novel data sources easier. Even though data collection via the internet is convenient, regular visits to the website hosting the high-score boards were needed in this study. Web-crawling technology can be used to further automate the process of accessing and downloading data from websites (Khalil & Fakir 2017). However, setting up and running web-crawlers reliably does require substantial expertise. If these tools become more accessible for researchers, the effort required to gather data could be reduced further. In some instances, it might be possible to enter a direct cooperation with the data owners, who could then provide the data in an agreed-upon format. This way, more reliable data that needs less wrangling could be acquired.

The growing popularity of outdoor climbing raises concerns about the sport’s impact on cliffside ecosystems (Holzschuh 2016). In the second manuscript included in this thesis, “The Physical Damage of Climbing Activity on Sandstone Lichen Cover”, I quantify damages caused by climbing activity. Lichen fulfill a number of useful functions for their ecosystem, providing protection and fixation to their substrate and serving as food for higher order taxa. The fact that climbing activity affects cliffside vegetation is known (Clark & Hessl 2015), although there are contrasting results in the literature. This could be the consequence of natural biotic and abiotic variation, which can lead studies to yield varying results, and provides a potential source for selection bias (Holzschuh 2016). This highlights the impact subtle differences between similar ecosystems can have and shows that results have to be vetted carefully before being applied to a different context, e.g. the resolution of a conflict.

My study subject was a previously unscaled boulder, which was climbed 500 times as part of the study. I investigated changes on the boulders surface over the course of this study, especially at the holds used. Since the study was conducted at a single boulder instead of comparing sites, I circumnavigated potential issues raised by biotic and abiotic variation. For each ascent, the same holds were used consistently for hands and feet, and photographs of every hold were taken at predetermined intervals. This follows a well-established, standardized experimental protocol to quantify the resistance of vegetation against a disturbance (source aus paper: Cole & Neil 1993). I find that the lichen cover deteriorates in holds used with feet, but not in holds used exclusively with hands. This suggests that the damaging process is different for hand- and footholds, which is in line with mechanical differences between the use of hands and feet when climbing: Climbing shoe soles are less elastic and made from a more abrasive material than skin, and feet are less precisely positioned while carrying more of the climber's weight. Regarding the progression of damage over repeated ascents, I find that the relative lichen cover reduces rapidly with the onset of climbing activity and stabilizes to some degree after about 50-100 ascents. These results indicate that the impact of climbing on lichen is mostly caused by rock abrasion. Most lichen seal off their substrate and form a protective layer that prevents erosion (Steinbauer et al. 2013). Abrasion caused by climbing activity could therefore have a second order effect by removing this protective layer. From these results, we derive a clear recommendation for evidence-based conservation efforts: Damages to the lichen cover happen at the onset of climbing activity. After this initial loss of lichen cover, the number and frequency of climbers have no further significant impact on it. Taking this into account, climbing activity should be directed to designated sites, while climbing pristine cliff sites should be discouraged. The overall aim would be for few cliff sites to be climbed often, instead of many cliff sites to be climbed seldom.

For this study, I conducted an active field study where a subject was submitted to a controlled treatment repeatedly while documenting changes induced by the treatment. This method eliminates the majority of confounding variables and ensures that observed changes are due to the treatment. Being a standardized experimental protocol, there are few questions to its proper execution and data analysis. This allows for easy replication in different contexts, e.g. repeating our study on a different substrate. Treatments have to be applied repeatedly and in a short amount of time, to exclude most environmental factors, such as changes in weather patterns. Moreover, the course of the study subjects the ecosystem to possible disturbances in excess of the status quo. As such, this kind of method is ill-suited to study rare ecosystems or the impact of drastic treatments. Despite these methodical drawbacks, it is the best suited method in this instance. It provides a way to control confounding variables and isolate the effect of the climbing activity effectively. The trade-offs between the strain on the ecosystem caused by the study and the insights gained, which help design evidence-based management measures, come out in favor of the experiment. This can be argued ahead of time because the study follows a well-established method, for which the course and effects are predictable and which is known to provide robust results.

"The influence of recreational activities on temporal feeding patterns of the common kingfisher (*Alcedo atthis*)" is the third manuscript we present. It contains efforts to quantify the impact of recreational activity on common kingfishers by direct observations. The common kingfisher is a flagship species that garners public attention for conservation efforts. Furthermore, the common kingfisher serves as an indicator for the effects of human activity on wildlife overall, because their high mobility allows them to evade easily (Suri et al. 2017). They are classified as vulnerable in Germany (European Environment Agency 2019) and considered to be endangered in Bavaria (Bayerisches Landesamt für Umwelt 2022). Disturbances are particularly critical during the birds' breeding and rearing period, where they can have an impact on species-level well-being by reducing reproductive success, potentially even leading to abandoned broods. It is known that birds react to disturbances with partial or complete nest abandonment or reduced nest attentiveness, which increases predation risk (Hockin et al. 1992, Baudains & Lloyd 2007, Bötsch et al. 2017). However, there are studies showing habituation adaptations, e.g. shifting feeding behaviour to other daytimes (Hockin et al. 1992, Baudains & Lloyd 2007). I aim to provide insight into which human activities are tolerable for common kingfisher and which are critical and must therefore be reduced via management measures.

This study was conducted at four different sites, with different frequencies and types of human activities. The sites ranged from a popular park to remote rural stream segments along the river Regnitz. Research assistants observed the birds' behavior and human activity directly from a distance. Observers took precautions to not interfere with the observed subjects, using appropriate gear such as binoculars and camouflage tents. They monitored the nests for a total of 213 hours across 25 days, recording for each minute whether a bird was entering the nest or perching nearby, as well as any human activities taking place in the vicinity. It was not possible to record reliably whether birds entering their nests carried food items. Therefore, nest-entering events were decided on as proxies for feeding activity. For my analysis, I used generalized linear models on two different granularities: I modeled the likelihood of a bird entering its nest minute-wise and the count of nest-entering events aggregated by hours as dependent variable, using human activities and other factors such as temperature as independent variables. A model selection procedure then revealed whether the observed human activities had a significant effect on the birds' behaviour. Moreover, this modelling approach allows to estimate the magnitude of the impact the disturbances have, by evaluating the modelled dependencies in the absence of any disturbance. The minute-wise analysis captures situations where the bird delays its approach to the nest when disturbed, while such an adaptation has significantly lower impact on the hour-wise analysis. I find that immediate human presence reduces the likelihood of a bird entering its nest or perching nearby, albeit the total number of nest entries remains largely unaffected. While the immediate effect is significant, its magnitude is small. I find at most a 6% increase in nest-entering events in the absence of human activity from our models. My study differentiates between different kinds of human activities as well as their proximities to the nest, allowing to gain insight into what parameters make a human activity disturbing for the birds. I find that speed (such as in biking), proximity to the nest and loud noises (such as music being played) have the strongest impact on bird behaviour. Additionally, at the study site with the highest frequency of human activities, I find potential signs of habituation to humans.

Direct observation is a well-established quantitative method in ecology. For the success of an observational study, it is important to minimize the impact the observer has on the study subjects. Therefore, well-defined protocols on how to conduct observations are in place and specialized gear is available to blend into the surroundings and to observe from a distance. The protocols also aim to reduce differences in results from different observers, which can be a source of bias in the data if not managed well. Having observers on-site has the advantage that they can record and report about occurrences that are not part of the original study design. It is always possible for irregular events to occur, such as the mowing of a nearby lawn or tree maintenance. These events can affect study subject behaviour but remain undetected by remote sensing methods, such as camera traps. Direct observation is very resource-intensive, though. Researchers need to be on-site for the whole observation time. For remote locations, a relevant amount of time is also needed to access the site in the first place. If observations at dawn or dusk are necessary, observers may need to stay the night on-site or at a nearby location. The success of a direct observation study is directly linked to the available budget: the number of employed observers dictates how fragmented the collected data is. With an unlimited budget, enough observers can be financed to collect data without gaps, which improves the statistical significance of findings.

The fourth paper presented in this thesis is titled "Overcoming the challenge of remotely monitoring small birds using video traps and artificial intelligence: An example with the common kingfisher *Alcedo atthis*". In it, I use a remote setup to monitor a common kingfisher nesting site continuously. Remote wildlife monitoring is an alternative approach to direct observation, with a variety of methods available to allow for the study of different aspects of animal behaviour. One option for this are tags, which are attached to or ingested by individuals. They can provide a range of data types, such as location, acceleration or local temperature. However, their use falls under animal experimentation regulation, and animal welfare considerations such as weight, size and attachment method need to be taken into account (Hawkins 2004, Wilson & McMahon 2006, McMahon et al. 2008). Additionally, tags can be costly depending on their size, weight and capabilities. These factors make the use of tags especially challenging when applied to species with a small body weight and high mobility, such as birds. Instead of monitoring individuals, it is also possible to monitor locations. A tried and tested method to assess the regional species composition is monitoring via camera traps at a key site (Magioli et al. 2023). The recorded images can be analyzed manually, but automated image classification is becoming more readily available (Beery et al. 2019). Typically, camera traps trigger via motion sensors and take a short sequence of images when activated. The exact trigger parameters are adjustable to some degree. This dictates a certain window which kind of studies or species can be observed successfully via camera traps. In particular, small animals are difficult to capture reliably (Kelly 2008, Anile & Devillard 2016, Urlus et al. 2014).

In my study, I designed a fully off-the-grid video trap setup to record the study site continuously. For this, I deployed a dome camera in proximity to a common kingfisher nesting site at the river Regnitz. Electric power was supplied by a car battery, which was topped off using solar panels. The set-up recorded from dawn to dusk without interruption, streaming the recordings to a lab computer using the internet via cellular network, and saving them on disk. I deployed the camera setup from 17th May 2022 to 14th June 2022, capturing a total of 580 hours of footage. Reviewing such a volume of data is challenging if done manually. I therefore developed a bespoke computer vision model on a subset of the data. Our model is able to identify video frames that show a common kingfisher - we used it to analyze the full dataset. Subsequently, I constructed events of common kingfisher presence by clustering together frames with common kingfisher that are less than five seconds apart. This straight-forward procedure was successful in determining phases of common kingfisher presence and absence at the nesting site. Additionally, in order to show a possible application of our setup, I deployed a regular camera trap on the same riverbank to capture recreational traffic. A physical filter on the lens of the camera trap ensured the recorded images were anonymous. If the datasets from the video trap and the camera trap were combined, fine-grained insight into the behaviour of common kingfisher in presence of e.g. paddling activity could be gained. The execution of such a correlation analysis was beyond the scope of our study.

Camera traps are a mainstay of remote wildlife monitoring. Given their widespread use and researchers experience with this method, related technologies and operation procedures are advanced. It is well-known what the capabilities, limitations and required conditions are to employ camera traps in a study. Video traps are useful tools to go beyond the limitations of camera traps and the trigger mechanisms they require, but can be challenging to deploy in remote locations. My setup worked fully off-the-grid and only required cellular network to be present. This means no power outlet or wired internet connectivity was required. A key challenge in working with videos is the volume of data that needs to be analyzed. Since reviewing the captured footage manually is a huge effort, computer vision approaches are called for. The field of computer vision has advanced greatly in capabilities and ease of use in the past decade, and some ready to use solutions for ecological applications are available (Beery et al. 2019). These focus on the most common use case, though, and therefore work best on regular camera trap images. For my footage, no appropriate tool was available and I developed a bespoke deep learning computer vision algorithm. Entry-level knowledge and standard methods of machine learning would suffice to do so. Training resources geared towards ecological applications of computer vision would be helpful to make this technology easier to employ. Nonetheless, the possibility to deploy a video camera setup remotely that captures uninterrupted footage at a site, and to analyze that footage automatically, opens up an array of new wildlife monitoring opportunities.

"No effects of paddle strokes on hatching rates of later developmental stages of river trout *Salmo trutta fario*" is the fifth and final manuscript included in this thesis. It describes my laboratory experiment to study the impact paddling activity has on spawn of river trout. It therefore shares a topic with the manuscripts on the reproductive success of common kingfishers, namely studying the impact of recreational activity on the ecology of river ecosystems, but uses a different method and model organism. While the common kingfisher is a flagship species that garners public attention easily, river trout are an indicator species. Even though their conservation is classified as least concern by the IUCN (IUCN 2012), their well-being is tied to an overall healthy ecosystem. River trout need flowing water with a high oxygen content and loose gravel substrate to procreate successfully. Claims that paddling activity is contributing to reduced fish spawn rates are raised with little scientific evidence (Zauner & Ratschan 2004). The simultaneous rise in recreational activity and reduced reproductive success could be a mere coincidence, since there are a number of factors affecting spawn rates, such as growing sediment input from increasing agricultural activity. My experiment aims to clarify whether paddling strokes impair spawn physically, thereby reducing hatching rates. In order to avoid a biased study design, I include paddle strokes as well as sediment input as controlled factors and investigate their impact on larval development.

The study setup consisted of six study groups, each consisting of five water tanks that received the same treatment. Every tank hosted approximately 1000 fertilized eggs of river trout *Salmo trutta fario*. I took great care to provide the spawn with controlled, appropriate conditions for its development by providing a gravel substrate of appropriate grain size and conducting the entire experiment in a cooling chamber to manage the temperature, aiming to approximate water temperatures during river trout spawning season. The treatments were combinations of light or strong paddle strokes with or without the addition of a sediment solution. This results in six combinations of paddle strokes (none / light / strong) and sediment addition (none / 10g), which includes a control group that does not receive any treatment at all. Light paddle strokes only moved the water column, but did not make contact with the substrate, while strong paddle strokes hit into the substrate directly. I built two custom paddling devices that fitted on the rim of the tanks, in order to make paddle strokes reproducible and to ensure light paddle strokes stayed clear of the substrate. I applied treatments daily and exchanged water in the tanks every other day. Before applying treatments, I counted the number of live larvae, dead eggs and eggs or larvae presenting a fungal growth in each tank. The two latter were removed from their tanks and discarded. From day ten on, there were too many hatched larvae in the tanks to count without removing them, so I estimated their number. The study ended on day 16, when all larvae had hatched and the oldest were beginning to fill their swimming bladder with air. From this point on, the animals are legally considered to be fish, requiring an additional permit to continue experimentation and a more complex environment. I therefore ended the experiment on this day and counted the number of live larvae in all tanks exactly. While I find some statistical differences in hatching rates and development of fungal growths between individual groups, these differences do not persist systematically over time or treatment gradients. I conclude that there is no evidence that paddling activity negatively influences the development of river trout spawn.

Laboratory experiments offer a lot of control over the parameters of the study. This is because the environment is strictly controlled and designed to eliminate as many factors influencing the study subject as possible. Additionally, treatments are applied in a controlled and repeatable manner, and treatment groups can be cleanly separated. This makes it much easier to establish a link between the treatment and whatever effect (or lack thereof) is observed in the study. This is in contrast to observational studies or field experiments, where a plethora of other effects can cause a difference in behaviour of otherwise similar study sites. In ecology, controlled experiments are an established method, e.g. food selection studies are used to uncover hints of habituation of squirrels to urban environments (Wist et al. 2022). The simplification of the natural environment for a laboratory study comes with challenges, though. Creating an artificial system that allows the study subjects to develop or behave naturally requires a deep understanding of their needs and the equipment to fulfil these needs in a controlled manner (Kohler 2002). In my case, this meant conducting the experiment in a cooling chamber, which introduced logistical challenges and introduced a limit on the number of treatments and repetitions in each treatment due to space constraints. Moreover, by being a simplified model of a natural ecosystem, there are by definition crucial differences between the laboratory setup and the natural environment. Whether results obtained in the lab can be transferred to the wild and conclusions be generalized requires careful argumentation (Kohler 2002). In the example of food selection studies, captured individuals might be trap-happy and represent a biased sample of the population (Wist et al. 2022). Despite these challenges, laboratory experiments are crucial tools since they allow keeping the majority of parameters fixed across controlled treatment. This creates the opportunity to quantify the effects the treatments have on the study subjects in isolation. Additionally, laboratory experiments enable tests that would affect the natural ecosystem too drastically, as in toxicological studies.

Discussion

In this thesis, I demonstrate the application of various quantitative methods to sports ecology. Sports ecology is an interdisciplinary field at the intersection of sports studies and ecology – which can contribute to both nature conservation and society. Beyond academic interest, studying the effects of human outdoor activity on nature allows for management measures to be based on facts and knowledge instead of anecdotal experience.

When a conflict in outdoor activity, that involves ecological concerns, requires mediation, a factual basis is of particular importance. Riverine paddling is an example for an activity, whose ecological impact raises concerns. Three of the manuscripts included in this thesis are dedicated to quantifying aspects of the impact paddling activity has on the river ecosystem. The main conflicting groups involved here are paddlers and fishers. Fishers raise concerns about fish and bird species being impacted by the paddling activity and push for bans or restrictions thereof (VG Bayreuth 2009, dpa 2010, Amtmann 2024). At the same time, fishers feel disturbed by paddlers in pursuing their fishing hobby, which is a personal motivation to lobby for management measures. In this case, it is crucial to substantiate or rebut the ecological concerns, such that the discussion of the shared use of the river ecosystem can proceed with a common understanding of the facts. It is important that ecological concerns brought forward are not diminished by coincidental personal motivations. The role of sports ecology in mediating conflicts is to clarify the ecological impacts, such that a fair discussion can take place.

From my studies, I do not find clear evidence that moderate paddling activity has a relevant negative impact on the reproduction of common kingfisher *Alcedo atthis* and river trout *Salmo trutta fario.*

I studied the reactions of common kingfishers *Alcedo atthis* to nearby human activity, quantifying the degree to which different parameters of an activity affect the birds' behaviour. My results show that higher speeds, higher audible volume and long-lasting activities lead to stronger impacts on the birds' rate of nest entries. Paddling is a slow-moving activity that usually does not linger in locations for a long time. Applying these insights about common kingfishers' behaviour in presence of human activity to paddling, a threat to the reproductive success and long-term well-being of the species is not expected from a moderate degree of paddling activity. This conclusion follows from the hierarchical model of Tablado & Jenni (2017): since human activity does not significantly affect the individual birds' feeding pattern, it cannot influence the species in general, e.g. its population trends or its distribution. I also studied the impact paddle strokes have on the larval development of river trout *Salmo trutta fario*. In my experiment, paddling did not strongly affect the number of larvae that develop successfully, regardless of whether the paddle strokes only moved the water column or whether the paddle directly struck the substrate. Consequently, a moderate degree of paddling activity is not expected to pose a threat to the reproductive success and long-term well-being of river trout, either. These insights are interesting, in particular since in some cases a single instance of human activity can have a lasting impact on an ecosystem. This can be seen in the effect bouldering activity has on the lichen coverage of a cliff site. I studied this impact quantitatively and find that most of the damage to the lichen coverage is caused by the initial ascents, while further climbing activity extends the damage only marginally. Both, common kingfishers and river trout, seem to be tolerant of some paddling activity on the river, which is important to take into consideration should calls for outright bans or drastic limitations of paddling activity be voiced in discussions around the use of a body of water for recreational purposes.

This supports the results found in the literature that do not estimate paddling activity to be a high-disturbance activity (Batten 1977, Tuite et al. 1984, Platteeuw & Henkens 1997). Since they are highly mobile, volant birds are a suitable indicator to assess the effects of human activities on wildlife (Suri et al. 2017). Birds decide the potential threat to them by human activities based on several factors, e.g. visibility, shape, noise, direction, distance and, of particular importance, speed (Tuite et al. 1984, Klein et al. 1995, Platteeuw & Henkens 1997, Reichholf 1998, Glover et al. 2011 & 2015, Kruger 2016, Clausen et al. 2020). Hence, birds perceive people jogging to be more threatening than people promenading (Glover et al. 2011, Lethlean et al. 2017) – something I also saw in my study. Another effect I observed was how long-lasting activities in front of the nest decrease the common kingfisher activities at the nest, which is not commonly mentioned in the literature. Bird species assess threats differently due to their respective traits (Batten 1977, Tablado & Jenni 2017), for example Clausen et al. (2020) found a 34% increased energy expenditure in swans during kayaking. Overall, common kingfisher might be less sensitive to human activity due to some of its characteristics: It is a resident species, in contrast to migrating species (Burger & Gorchfeld

1991, Klein et al. 1995, Glover et al. 2011, MacGregor-Fors & Schondube 2011), and it breeds alone, in contrast to being part of a colony (Batten 1977, Laursen et al. 2005, Thiel et al. 2008, Glover et al. 2011). For birds, disturbances can lead to decreased nest attentiveness and partial or complete nest abandonment (Hockin et al. 1992; Baudains & Lloyd 2007; Bötsch et al. 2017; Zhang et al. 2017). However, some birds seem to habituate to potential disturbances (Hockin et al. 1992; Baudains & Lloyd 2007). This is particularly likely, when the potential disturbance is of a predictable or continuous nature (Platteeuw & Henkens 1997) – something I also observed in my study. While I found common kingfishers to react to human activity, they did not seem disrupted or hindered in their ability to hunt or feed their young. This is in accordance with Kipping (2018), who found that boating activity could interrupt common kingfishers' behaviour but leaves the general number of feedings largely unaffected. Despite having only minimal impact on common kingfishers, paddling activity can affect certain species (Bell et al. 2007; Stott 2019), e.g. drifting dragonfly larvae into untypical habitats (Schnorr 2000). Still, a number of worries have been voiced concerning paddling activity, which are lacking a sound scientific understanding so far (Zauner & Ratschan 2004): paddling activity might scare breeding birds or fish away, the mechanical contact of the paddle might damage spawn, the resulting turbidity might spark developmental disorders, fish might get hurt or sedimentation might increase. However, proper or experienced conduct avoids most mechanical impacts. This makes them indistinguishable from naturally occurring mechanical impacts, e.g. by debris or deluge (Zauner & Ratschan 2004). My findings are in agreement with this, since I did not find a significant impact of paddling activity in my study.

My conclusions regarding the impact of paddling on common kingfisher *Alcedo atthis* and river trout *Salmo trutta fario* are valid only for moderate degrees of paddling activity. If river sections are very popular and have near-constant paddling activity, I expect a stronger effect, as the activity is no longer passing by nests occasionally and paddle stroke effects under water possibly compound. Furthermore, I expect entry and exit points for paddling activity to affect species very differently from paddling activity that is already afloat on the body of water and simply passes through the habitat. Access points for paddling activity are typically managed actively by the authorities responsible, and unmanaged "wild" access points are usually unwelcome (Hennig 2011).

Given the wide range of interactions between outdoor sports and ecological systems, there are few standard procedures in sports ecology. Researchers draw on methods from the humanities (Wolf et al. 2011, Keul & Kühnberger 1997) and from ecology (Randler & Kalb 2018, McMahon et al. 2008) alike to execute studies. Identifying appropriate and feasible methods to study a given interaction is a challenge in itself. Every method comes with a set of trade-offs, some aspects being desirable but also presenting downsides, such as high cost in terms of material or human effort, requiring bespoke know-how for proper execution or causing a significant impact on the ecosystem being studied. For established methods, these trade-offs are well known. In the research presented, I conducted a field experiment, a lab experiment and an observational study. These are very different methods, each with their own strengths and challenges, but for all of them, it is well known how to execute them successfully. This methodical experience can mitigate their drawbacks to some degree. For example, direct observation studies require spending a lot of time in the field. This time effort can be delegated to e.g. student assistants by using established protocols, making sure the data collected is reliable and complete. This means the scientists leading the study have more time do dedicate to other tasks. When established methods fall short, novel methods can open new possibilities to study a subject, or make studies easier, cheaper or more reliable in their execution. Compared to established methods, novel methods typically come with more organisational uncertainty. In the research included in this thesis, I applied novel methods in two different ways.

I analysed data from Strava (Strava, Inc.), a social platform for sportspeople, with the aim of understanding the shift in cycling habits induced by epidemic-control-decisions due to the COVID-19 pandemic. Using data that was not originally gathered for the study at hand is a novel approach. A more established alternative would be to use questionnaires (Wolf 2009, Wolf et al. 2011), or manually counting events at the locations (Hartmann 1988, Murphy 1992, Keul & Kühnberger 1997), in this case cyclists on paths. With these approaches, studying behavioural shifts in different regions across Germany would have required a tremendous amount of organisational effort. Furthermore, it would not have been possible to include observations of periods before the start of the study, which I was able to do based on historic data from Strava. At the same time, analysing the raw data appropriately required a lot of care. Separating recreational cycling from commuting, as well as identifying and handling a variety of possible biases in the dataset, was callenging. More guidelines on how to manage such “unclean” datasets in order to obtain reliable data and a reproducible result would have been very useful.

In another project, I deployed video cameras to observe the common kingfisher *Alcedo atthis* remotely, in the context of paddling activity. Small birds are challenging to monitor remotely since they are hard to capture reliably with triggers used commonly in camera traps (Randler & Kalb 2018, see also: Anile & Devillard 2016). Other methods of remote monitoring for wildlife, such as tags attached to the animal, are challenging to apply here due to the small weight and the specific mobility requirements of the species (Hawkins 2004, Wilson & McMahon 2006, McMahon et al. 2008). My video camera setup overcomes the need for a trigger, which is the limiting factor in the established method. The trade-off is that a huge amount of data is captured and needs to be reviewed. This work intensive step can be automated using modern computer vision techniques, by creating a bespoke AI model to detect the presence of a bird in the recorded videos. This way, the physical trigger of commonly used camera traps is replaced by a post-hoc, content-based trigger. Using this novel method of wildlife monitoring meant working around several open questions regarding the analysis of the videos. Critically, it was not clear which approach can successfully detect common kingfishers in the recorded footage.

From my studies, I find that novel methods focusing on digitalization hold great potential for the quantitative study of the impact of outdoor sport on ecological systems. Utilizing new data sources and automating formerly manual tasks proofed useful in my research.

A commonality between the novel approaches applied in the research for this thesis is that they are both very data-centric – direct human effort in data collection is substituted with effort and uncertainties in handling the data itself. For these methods to become more common, the effort and uncertainties need to be reduced. If third-party data becomes a more common source of information, steps towards agreed-upon categories of bias to be aware of, methods to identify and counteract them and metrics to possibly quantify them would help researchers to show the robustness of their conclusions in a straightforward way. This reduces the uncertainty how to properly handle potentially “unclean” data. Another opportunity for improvement is extend tooling and teaching material that is geared towards ecological application of AI. Some general tools exist, focussing on the most common applications (Beery et al. 2019). Creating and evaluating bespoke models holds great potential for visual data (Pegoraro et al. 2020), but requires expert input. By making this expertise, or at least knowledge about its potential and requirements for its application, more available to ecologists, studies with visual data would become easier to conduct. In some cases, such as with video traps, the expertise can even be key to unlocking new study setups that previously had to be dismissed due to the large effort required for data analysis.

The main opportunity in digitalized and automated study designs is that it is possible to apply them on a large scale. I was able to study changes in behaviour across Germany by using social media data. Automated visual data analysis greatly reduces the effort associated with camera trap studies, even making video traps practically feasible. A standardized setup and data evaluation could allow replicating a camera-based study on a wide range of similar ecosystems, e.g. studying the impact paddling activity has on riverine birds' feeding behaviour on rivers across Germany. Such a cross-sectional study would allow to derive more widely applicable insights and avoid the challenges associated with applying results across sites (Buma 2021). Therefore, standards, knowledge and tooling around the application of novel approaches should be promoted in the field.

The research conducted for this thesis employs a variety of methods to quantify the effects of outdoor sport on ecological systems. No one method is better suited for this task than another. Instead, the best method depends on the study setup and resources available. Using established methods tends to be more resource intensive than the particular novel methods we applied, but offers the collective experience in applying the method to navigate uncertainties surrounding the study. Among other factors, this could be working with less experienced help, justifying expenses or filing for permissions to execute a study. The novel methods I applied came with a significant degree of methodical uncertainty: How, if at all, can this method be used to obtain relevant results? Still, it is worthwhile to use these methods and start to chip away at that uncertainty. The novel methods I applied allowed me to study effects that would not have been possible to quantify with more established means.

There is a plethora of interactions between outdoor sport and ecological systems that need to be studied to allow people to reap the benefits of being active outdoors while protecting ecosystems from undue consequences. Making use of the digitalization of society and opportunities for automation can reduce the effort needed to study interactions. In tandem, these two methodologies present the possibility to scale up quantitative insights and provide a sound scientific understanding for discussions and management measures.

Manuscripts of this thesis

All five manuscripts included in this thesis investigate the effects of outdoor activities on natural systems. For this, mostly direct and immediate variables were used and analysed in the context of their chronology. Kindly note that all manuskripts contained in this dissertation are a collaboration of my colleagues and me. A detailed break-down of my specific contributions to each manuscript can be found in the paragraph “List of manuscripts included in this dissertation & declarations of contributions”. For brevity, in the body of this dissertation first person singular is used throughout.

In manuscript 1, I examine changes in human outdoor behaviour during lockdown due to the COVID-19 pandemic in Germany. For this, I use cycling data as a proxy for sportive outdoor behaviour. This manuscript is the first to use fitness and outdoor apps as management tools to discern the volume of sportive cycling traffic in urban, rural and conserved areas. In the manuscript, I also demonstrate the importance of green spaces and the need for physical activity and the outdoors.

Manuscript 2 covers a conflict around outdoor bouldering and climbing, namely the impact and magnitude of climbing activities at newly climbed sites. Although this conflict has been discussed on different levels, this manuscript is the first to document abrasions caused by climbing activity meticulously: I assessed a previously unclimbed boulder before, during and after 500 climbing ascents. My findings lead to a straightforward management recommendation that could solve the main point of conflict concerning climbing and bouldering activity and nature conservation.

Starting with manuscript 3, all following studies examine the effect of paddling activity to some extent. Manuscript 3 investigates the effects of paddling activities on the feeding patterns of common kingfishers *Alcedo atthis* during breeding season. Common kingfishers are often depicted as a shy species in need of protection from human influences. In contrast, I found that human activity had a minimal effect on the birds’ feeding pattern in my study. At sites with particularly high human activity, the birds showed signs of habituation. However, since the data for manuscript 3 has been gathered by direct observations, no location had been observed for the entire breeding and feeding period continually.

For manuscript 4, I installed off-the-grid video traps that filmed the entrance of the nest of common kingfisher continually for one entire brood. As far as I am aware, this manuscript is the first to stream the events at a nest entrance of common kingfisher remotely. I then employed modern machine learning techniques to recognize video frames showing common kingfisher, and automated the classification process of these video frames. In my manuscript, I show how these results can be combined with other data and possible future uses of our setup.

In manuscript 5, I investigated the effects of paddling activity on fish spawn development in river habitats, using river trout *Salmo trutta fario* as our model organism. I conducted this experiment in a cooling chamber. The fish spawn was divided into tanks, which were in turn divided into treatment groups. I found no negative effect on hatching rates due to paddling treatment, and only minor effects on the development of fungal growths. In my manuscript, I discuss the benefits and drawbacks of laboratory conditions and experiments in natural settings.

References

Alaei, A. R., S. Becken, and B. Stantic. 2019. Sentiment Analysis in Tourism: Capitalizing on Big Data. *Journal of Travel Research* 58: 175–191. doi:10.1177/0047287517747753.

Alexandrino, E. R., E. R. Buechley, A. J. Piratelli, K. M. P. M. de B. Ferraz, R. de Andrade Moral, Ç. H. Şekercioğlu, W. R. Silva, and H. T. Z. do Couto. 2016. Bird sensitivity to disturbance as an indicator of forest patch conditions: An issue in environmental assessments. *Ecological Indicators* 66: 369–381. doi:10.1016/j.ecolind.2016.02.006.

Amtmann, K. 2024. „Gefahr für Leben und Gesundheit“: Streit ums Paddeln auf Bayerns Flüssen. *Merkur.de*.

Anile, S., and S. Devillard. 2016. Study design and body mass influence RAIs from camera trap studies: evidence from the Felidae: Factors affecting camera-trapping success rate across felids. *Animal Conservation* 19: 35–45. doi:10.1111/acv.12214.

Arlettaz, R., P. Patthey, M. Baltic, T. Leu, M. Schaub, R. Palme, and S. Jenni-Eiermann. 2007. Spreading free-riding snow sports represent a novel serious threat for wildlife. *Proceedings of the Royal Society B: Biological Sciences* 274: 1219–1224. doi:10.1098/rspb.2006.0434.

Arnegård, J., and K. Sandell. 2012. Outdoor recreation in times of change.

Aubé, M. 2015. Physical behaviour of anthropogenic light propagation into the nocturnal environment. *Philosophical Transactions of the Royal Society B: Biological Sciences* 370: 20140117. doi:10.1098/rstb.2014.0117.

Balmford, A., J. M. H. Green, M. Anderson, J. Beresford, C. Huang, R. Naidoo, M. Walpole, and A. Manica. 2015. Walk on the Wild Side: Estimating the Global Magnitude of Visits to Protected Areas. *PLOS Biology* 13: e1002074. doi:10.1371/journal.pbio.1002074.

Banks, P. B., and J. V. Bryant. 2007. Four-legged friend or foe? Dog walking displaces native birds from natural areas. *Biology Letters* 3: 611–613. doi:10.1098/rsbl.2007.0374.

Barnosky, A. D., N. Matzke, S. Tomiya, G. O. U. Wogan, B. Swartz, T. B. Quental, C. Marshall, J. L. McGuire, et al. 2011. Has the Earth’s sixth mass extinction already arrived? *Nature* 471: 51–57. doi:10.1038/nature09678.

Batten, L. A. 1977. Sailing on reservoirs and its effects on water birds. *Biological Conservation* 11: 49–58. doi:10.1016/0006-3207(77)90027-1.

Baudains, T. P., and P. Lloyd. 2007. Habituation and habitat changes can moderate the impacts of human disturbance on shorebird breeding performance. *Animal Conservation* 10: 400–407. doi:10.1111/j.1469-1795.2007.00126.x.

Bayerisches Landesamt für Umwelt. 2022. Eisvogel (Alcedo atthis).

Beale, C. M., and P. Monaghan. 2005. Modeling the Effects of Limiting the Number of Visitors on Failure Rates of Seabird Nests. *Conservation Biology* 19: 2015–2019. doi:10.1111/j.1523-1739.2005.00256.x.

Beery, S., D. Morris, and S. Yang. 2019. Efficient Pipeline for Camera Trap Image Review (version 1). arXiv. doi:10.48550/ARXIV.1907.06772.

Behutiye, W., P. Karhapää, L. Lopez, X. Burgues, S. Martinez-Fernandez, A. M. Vollmer, P. Rodriiguez, X. Franch, et al. 2020. Management of quality requirements in agile and rapid software development: A systematic mapping study. *Information and Software Technology* 123: 106225. doi:10.1016/j.infsof.2019.106225.

Bell, S., L. Tyrväinen, T. Sievänen, U. Pröbstl, and M. Simpson. 2007. Outdoor Recreation and Nature Tourism: A European Perspective. *Living Reviews in Landscape Research* 1. doi:10.12942/lrlr-2007-2.

Bennie, J., T. W. Davies, D. Cruse, R. Inger, and K. J. Gaston. 2015. Cascading effects of artificial light at night: resource-mediated control of herbivores in a grassland ecosystem. *Philosophical Transactions of the Royal Society B: Biological Sciences* 370: 20140131. doi:10.1098/rstb.2014.0131.

Bhatia, S., S. M. Redpath, K. Suryawanshi, and C. Mishra. 2020. Beyond conflict: exploring the spectrum of human–wildlife interactions and their underlying mechanisms. *Oryx* 54: 621–628. doi:10.1017/S003060531800159X.

BMU Beirat. 2020. NACHHALTIGER SPORT 2030 – Verantwortung für Natur, Umwelt und Gesellschaft. Beirat „Umwelt und Sport" beim Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU).

BMUV. 2023. Politik des BMUV für Nachhaltigkeit im Sport. January 30.

BMUV Members of the Advisory Board. 2021. SUSTAINABLE SPORT 2030 – Responsibility for Nature, the Environment and Society. BMUV Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

Bötsch, Y., Z. Tablado, and L. Jenni. 2017. Experimental evidence of human recreational disturbance effects on bird-territory establishment. *Proceedings of the Royal Society B: Biological Sciences* 284: 20170846. doi:10.1098/rspb.2017.0846.

Bowler, D. E., L. M. Buyung-Ali, T. M. Knight, and A. S. Pullin. 2010. A systematic review of evidence for the added benefits to health of exposure to natural environments. *BMC Public Health* 10: 456. doi:10.1186/1471-2458-10-456.

Braunisch, V., P. Patthey, and R. Arlettaz. 2011. Spatially explicit modeling of conflict zones between wildlife and snow sports: prioritizing areas for winter refuges. *Ecological Applications* 21: 955–967. doi:10.1890/09-2167.1.

Brown, G., and R. Mendelsohn. 1984. The Hedonic Travel Cost Method. *The Review of Economics and Statistics* 66: 427. doi:10.2307/1924998.

Buma, B. 2021. Disturbance ecology and the problem of $n = 1$: A proposed framework for unifying disturbance ecology studies to address theory across multiple ecological systems. *Methods in Ecology and Evolution* 12: 2276–2286. doi:10.1111/2041-210X.13702.

Bundesumweltministerium. 2021. Politik des BMUV für Nachhaltigkeit im Sport.

Calogiuri, G., and L. Elliott. 2017. Why Do People Exercise in Natural Environments? Norwegian Adults' Motives for Nature-, Gym-, and Sports-Based Exercise. *International Journal of Environmental Research and Public Health* 14: 377. doi:10.3390/ijerph14040377.

Cambridge Advanced Learner´s Dictionary & Thesaurus. 2024. nature. *Cambridge Advanced Learner´s Dictionary & Thesaurus*. Cambridge University Press. https://dictionary.cambridge.org/dictionary/english/nature. Accessed September 10.

Carter, N. H., B. K. Shrestha, J. B. Karki, N. M. B. Pradhan, and J. Liu. 2012. Coexistence between wildlife and humans at fine spatial scales. *Proceedings of the National Academy of Sciences* 109: 15360–15365. doi:10.1073/pnas.1210490109.

Ceballos, G., P. R. Ehrlich, A. D. Barnosky, A. García, R. M. Pringle, and T. M. Palmer. 2015. Accelerated modern human–induced species losses: Entering the sixth mass extinction. *Science Advances* 1: e1400253. doi:10.1126/sciadv.1400253.

Clark, P., and A. Hessl. 2015. The effects of rock climbing on cliff-face vegetation. Edited by Jürgen Dengler. *Applied Vegetation Science* 18: 705–715. doi:10.1111/avsc.12172.

Clausen, K. K., T. E. Holm, C. L. Pedersen, E. M. Jacobsen, and T. Bregnballe. 2020. Sharing waters: the impact of recreational kayaking on moulting mute swans Cygnus olor. *Journal of Ornithology* 161: 469–479. doi:10.1007/s10336-020-01746-z.

Cole, D. N., and N. G. Bayfield. 1993. Recreational trampling of vegetation: standard experimental procedures. *Biological Conservation* 63: 209–215. doi:10.1016/0006-3207(93)90714-C.

Council of Europe. 1992. Recommendation No. R (92) 13 REV of the Committee of Ministers to Member States on the revised European Sports Charter.

Cowie, R. H., P. Bouchet, and B. Fontaine. 2022. The Sixth Mass Extinction: fact, fiction or speculation? *Biological Reviews* 97: 640–663. doi:10.1111/brv.12816.

Davies, T. W., and T. Smyth. 2018. Why artificial light at night should be a focus for global change research in the 21st century. *Global Change Biology* 24: 872–882. doi:10.1111/gcb.13927.

De Vos, J. M., L. N. Joppa, J. L. Gittleman, P. R. Stephens, and S. L. Pimm. 2015. Estimating the normal background rate of species extinction: Background Rate of Extinction. *Conservation Biology* 29: 452–462. doi:10.1111/cobi.12380.

dpa. 2010. Paddler und Angler streiten um Fluss. *Merkur.de*.

Ducarme, F., and D. Couvet. 2020. What does ‘nature’ mean? *Palgrave Communications* 6: 14. doi:10.1057/s41599-020-0390-y.

Ellis, E. C., N. Gauthier, K. Klein Goldewijk, R. Bliege Bird, N. Boivin, S. Díaz, D. Q. Fuller, J. L. Gill, et al. 2021. People have shaped most of terrestrial nature for at least 12,000 years. *Proceedings of the National Academy of Sciences* 118: e2023483118. doi:10.1073/pnas.2023483118.

Engemann, K., C. B. Pedersen, L. Arge, C. Tsirogiannis, P. B. Mortensen, and J.-C. Svenning. 2019. Residential green space in childhood is associated with lower risk of psychiatric disorders from adolescence into adulthood. *Proceedings of the National Academy of Sciences* 116: 5188–5193. doi:10.1073/pnas.1807504116.

European Environment Agency. 2019. Kingfisher - Alcedo Atthis - (Linnaeus, 1758).

Feldman, R. 2013. Techniques and applications for sentiment analysis. *Communications of the ACM* 56: 82–89. doi:10.1145/2436256.2436274.

Filippini, M., W. Greene, and A. L. Martinez-Cruz. 2018. Non-market Value of Winter Outdoor Recreation in the Swiss Alps: The Case of Val Bedretto. *Environmental and Resource Economics* 71: 729–754. doi:10.1007/s10640-017-0181-0.

Finney, S. K., J. W. Pearce-Higgins, and D. W. Yalden. 2005. The effect of recreational disturbance on an upland breeding bird, the golden plover Pluvialis apricaria. *Biological Conservation* 121: 53–63. doi:10.1016/j.biocon.2004.04.009.

Floyd, M. F., H. Jang, and F. P. Noe. 1997. The Relationship Between Environmental Concern and Acceptability of Environmental Impacts among Visitors to Two U.S. National Park Settings. *Journal of Environmental Management* 51: 391–412. doi:10.1006/jema.1997.0151.

Fong, K. C., J. E. Hart, and P. James. 2018. A Review of Epidemiologic Studies on Greenness and Health: Updated Literature Through 2017. *Current Environmental Health Reports* 5: 77–87. doi:10.1007/s40572-018-0179-y.

Frid, A., and L. M. Dill. 2002. Human-caused Disturbance Stimuli as a Form of Predation Risk. *Conservation Ecology* 6: art11. doi:10.5751/ES-00404-060111.

George, S. L., and K. R. Crooks. 2006. Recreation and large mammal activity in an urban nature reserve. *Biological Conservation* 133: 107–117. doi:10.1016/j.biocon.2006.05.024.

Gill, J. A. 2007. Approaches to measuring the effects of human disturbance on birds: Measuring the effects of human disturbance on birds. *Ibis* 149: 9–14. doi:10.1111/j.1474-919X.2007.00642.x.

GWS, G. Ahlert, S. Repenning, I. an der Heiden, and 2HMforum. Gmbh. Die ökonomische Bedeutung des Sports in Deutschland – Sportsatellitenkonto (SSK) 2018. Gesellschaft für Wirtschaftliche Strukturforschung mbH (GWS).

Haines-Young, R., and M. Potschin. 2010. The links between biodiversity, ecosystem services and human well-being. In *Ecosystem Ecology*, ed. D. G. Raffaelli and C. L. J. Frid, 1st ed., 110–139. Cambridge University Press. doi:10.1017/CBO9780511750458.007.

Hamstead, Z. A., D. Fisher, R. T. Ilieva, S. A. Wood, T. McPhearson, and P. Kremer. 2018. Geolocated social media as a rapid indicator of park visitation and equitable park access. *Computers, Environment and Urban Systems* 72: 38–50. doi:10.1016/j.compenvurbsys.2018.01.007.

Hartig, T., R. Mitchell, S. de Vries, and H. Frumkin. 2014. Nature and Health. *Annual Review of Public Health* 35: 207–228. doi:10.1146/annurev-publhealth-032013-182443.

Hartmann, R. 1988. Combining field methods in tourism research. *Annals of Tourism Research* 15: 88–105. doi:10.1016/0160-7383(88)90073-4.

Harvell, C. D., D. Montecino-Latorre, J. M. Caldwell, J. M. Burt, K. Bosley, A. Keller, S. F. Heron, A. K. Salomon, et al. 2019. Disease epidemic and a marine heat wave are associated with the continental-scale collapse of a pivotal predator (*Pycnopodia helianthoides*). *Science Advances* 5: eaau7042. doi:10.1126/sciadv.aau7042.

Hawkins, P. 2004. Bio-logging and anial welfare: practical refinements. *Mem Natl Inst Polar Res*: 58–68.

Heil, L., E. Fernández-Juricic, D. Renison, A. M. Cingolani, and D. T. Blumstein. 2007. Avian responses to tourism in the biogeographically isolated high Córdoba Mountains, Argentina. *Biodiversity and Conservation* 16: 1009–1026. doi:10.1007/s10531-006-9040-y.

Hennig, S., and M. Künzl. 2011. Applying Integrated Nature Conservation Management: Visitor Management and Monitoring of Winter Recreation Activities Focusing Grouse Species in Berchtesgaden National Park. In *Sustainable Development in Mountain Regions*, ed. G. Zhelezov, 239–253. Dordrecht: Springer Netherlands. doi:10.1007/978-94-007-0131-1_20.

Hockin, D., M. Ounsted, M. Gorman, D. Hill, V. Keller, and M. A. Barker. 1992. Examination of the effects of disturbance on birds with reference to its importance in ecological assessments. *Journal of Environmental Management* 36: 253–286. doi:10.1016/S0301-4797(08)80002-3.

Holzschuh, A. 2016. Does rock climbing threaten cliff biodiversity? - A critical review. *Biological Conservation* 204: 153–162. doi:10.1016/j.biocon.2016.10.010.

IUCN. 2010. Salmo trutta: Freyhof, J.: The IUCN Red List of Threatened Species 2013: e.T19861A9050312. International Union for Conservation of Nature. doi:10.2305/IUCN.UK.2008.RLTS.T19861A9050312.en.

Jacob, G. R., and R. Schreyer. 1980. Conflict in Outdoor Recreation: A Theoretical Perspective. *Journal of Leisure Research* 12: 368–380. doi:10.1080/00222216.1980.11969462.

Kahlmeier, S., T. Götschi, N. Cavill, C. Brand, A. C. Fernandez, D. Rojay Ruedas, J. Woodcock, P. Kelly, et al. 2017. Health economic assessment tool (HEAT) for walking and for cycling. World Health Organization Regional Office for Europe.

Kangas, K., M. Luoto, A. Ihantola, E. Tomppo, and P. Siikamäki. 2010. Recreation-induced changes in boreal bird communities in protected areas. *Ecological Applications* 20: 1775–1786. doi:10.1890/09-0399.1.

Kelly, M. J. 2008. Design, evaluate, refine: camera trap studies for elusive species. *Animal Conservation* 11: 182–184. doi:10.1111/j.1469-1795.2008.00179.x.

Keul, A., and A. Kühberger. 1997. Tracking the Salzburg tourist. *Annals of Tourism Research* 24: 1008–1012. doi:10.1016/S0160-7383(97)00038-8.

Khalil, S., and M. Fakir. 2017. RCrawler: An R package for parallel web crawling and scraping. *SoftwareX* 6: 98–106. doi:10.1016/j.softx.2017.04.004.

Klein, M. L., S. R. Humphrey, and H. F. Percival. 1995. Effects of Ecotourism on Distribution of Waterbirds in a Wildlife Refuge. *Conservation Biology* 9: 1454–1465. doi:10.1046/j.1523-1739.1995.09061454.x.

Kocifaj, M., and H. A. Solano Lamphar. 2014. Quantitative analysis of night skyglow amplification under cloudy conditions. *Monthly Notices of the Royal Astronomical Society* 443: 3665–3674. doi:10.1093/mnras/stu1301.

Kohler, R. E. 2002. *Landscapes & labscapes: exploring the lab-field border in biology*. Chicago: University of Chicago Press.

Kulczyk, S., E. Woźniak, and M. Derek. 2018. Landscape, facilities and visitors: An integrated model of recreational ecosystem services. *Ecosystem Services* 31: 491–501. doi:10.1016/j.ecoser.2018.02.016.

Kuwaczka, L. F., V. Mitterwallner, V. Audorff, and M. J. Steinbauer. 2023. Ecological impacts of (electrically assisted) mountain biking. *Global Ecology and Conservation* 44: e02475. doi:10.1016/j.gecco.2023.e02475.

Larson, C. L., S. E. Reed, A. M. Merenlender, and K. R. Crooks. 2016. Effects of Recreation on Animals Revealed as Widespread through a Global Systematic Review. Edited by Hideyuki Doi. *PLOS ONE* 11: e0167259. doi:10.1371/journal.pone.0167259.

Laursen, K., J. Kahlert, and J. Frikke. 2005. Factors affecting escape distances of staging waterbirds. *Wildlife Biology* 11: 13–19. doi:10.2981/0909-6396(2005)11[13:FAEDOS]2.0.CO;2.

Magioli, M., E. A. R. Carvalho, R. Sampaio, T. Püttker, S. Arlt, W. Hanoeman, R. Mattai, A. Ooms, et al. 2023. Mammal diversity and composition are not affected by certified timber extraction in Suriname. *Forest Ecology and Management* 541: 121080. doi:10.1016/j.foreco.2023.121080.

Mainini, B., P. Neuhaus, and P. Ingold. 1993. Behaviour of marmots marmota marmota under the influence of different hiking activities. *Biological Conservation* 64: 161–164. doi:10.1016/0006-3207(93)90653-I.

Manfredo, M., J. Vaske, B. Bruyere, D. Field, and P. Brown. 2004. *Society and Natural Resources: A Summary of Knowledge*. Jefferson: Modern Litho.

McCullough, B. P., N. A. Bergsgard, A. Collins, A. Muhar, and L. Tyrväinen. 2018. The Impact of Sport and Outdoor Recreation (Friluftsliv) on the Natural Environment.

McMahon, C. R., I. C. Field, C. J. A. Bradshaw, G. C. White, and M. A. Hindell. 2008. Tracking and data–logging devices attached to elephant seals do not affect individual mass gain or survival. *Journal of Experimental Marine Biology and Ecology* 360: 71–77. doi:10.1016/j.jembe.2008.03.012.

Milcu, A. I., J. Hanspach, D. Abson, and J. Fischer. 2013. Cultural Ecosystem Services: A Literature Review and Prospects for Future Research. *Ecology and Society* 18: art44. doi:10.5751/ES-05790-180344.

Millenium Ecosystem Assessment. 2005. *Ecosystems and human well-being: synthesis; a report of the Millennium Ecosystem Assessment*. The Millennium Ecosystem Assessment Series. Washington, DC: Island Press.

Mitterwallner, V., M. J. Steinbauer, A. Besold, A. Dreitz, M. Karl, N. Wachsmuth, V. Zügler, and V. Audorff. 2021. Electrically assisted mountain biking: Riding faster, higher, farther in natural mountain systems. *Journal of Outdoor Recreation and Tourism* 36: 100448. doi:10.1016/j.jort.2021.100448.

Moesch, C., S. Christen, and T. Ströbel. 2022. It's getting tight in the Alps - challenges and implications of the e-mountain bike boom for sustainable tourism management. *International Journal of Sport Management and Marketing* 22: 73. doi:10.1504/IJSMM.2022.121257.

Morton Turner, J. 2002. From Woodcraft to 'Leave No Trace': Wilderness, Consumerism, and Environmentalism in Twentieth-Century America. *Environmental History* 7: 462–482. doi:10.2307/3985918.

Müllner, A., K. Eduard Linsenmair, and M. Wikelski. 2004. Exposure to ecotourism reduces survival and affects stress response in hoatzin chicks (Opisthocomus hoazin). *Biological Conservation* 118: 549–558. doi:10.1016/j.biocon.2003.10.003.

Murphy, P. E. 1992. Urban Tourism and Visitor Behavior. *American Behavioral Scientist* 36: 200–211. doi:10.1177/0002764292036002007.

Naidoo, R., and A. C. Burton. 2020. Relative effects of recreational activities on a temperate terrestrial wildlife assemblage. *Conservation Science and Practice* 2. doi:10.1111/csp2.271.

Naylor, L. M., M. J. Wisdom, and R. G. Anthony. 2009. Behavioral Responses of North American Elk to Recreational Activity. *Journal of Wildlife Management* 73: 328–338. doi:10.2193/2008-102.

Noe, F. P., W. E. Hammitt, and R. D. Bixler. 1997. Park User Perceptions of Resource and Use Impacts Under Varied Situations in Three National Parks. *Journal of Environmental Management* 49: 323–336. doi:10.1006/jema.1995.0093.

Nyhus, P. J. 2016. Human–Wildlife Conflict and Coexistence. *Annual Review of Environment and Resources* 41: 143–171. doi:10.1146/annurev-environ-110615-085634.

Olson, L. E., J. R. Squires, E. K. Roberts, J. S. Ivan, and M. Hebblewhite. 2018. Sharing the same slope: Behavioral responses of a threatened mesocarnivore to motorized and nonmotorized winter recreation. *Ecology and Evolution* 8: 8555–8572. doi:10.1002/ece3.4382.

Pegoraro, L., O. Hidalgo, I. J. Leitch, J. Pellicer, and S. E. Barlow. 2020. Automated video monitoring of insect pollinators in the field. Edited by Alison Scott-Brown and Hauke Koch. *Emerging Topics in Life Sciences* 4: 87–97. doi:10.1042/ETLS20190074.

Pimm, S. L., C. N. Jenkins, R. Abell, T. M. Brooks, J. L. Gittleman, L. N. Joppa, P. H. Raven, C. M. Roberts, et al. 2014. The biodiversity of species and their rates of extinction, distribution, and protection. *Science* 344: 1246752. doi:10.1126/science.1246752.

Pinek, L., I. Mansour, M. Lakovic, M. Ryo, and M. C. Rillig. 2020. Rate of environmental change across scales in ecology. *Biological Reviews* 95: 1798–1811. doi:10.1111/brv.12639.

Pröbstl-Haider, U., D. Lund-Durlacher, H. Antonschmidt, and C. Hödl. 2018. Mountain bike tourism in Austria and the Alpine region – towards a sustainable model for multi-stakeholder product development. *Journal of Sustainable Tourism* 26: 567–582. doi:10.1080/09669582.2017.1361428.

Ramankutty, N., Z. Mehrabi, K. Waha, L. Jarvis, C. Kremen, M. Herrero, and L. H. Rieseberg. 2018. Trends in Global Agricultural Land Use: Implications for Environmental Health and Food Security. *Annual Review of Plant Biology* 69: 789–815. doi:10.1146/annurev-arplant-042817-040256.

Randler, C., and N. Kalb. 2018. Distance and size matters: A comparison of six wildlife camera traps and their usefulness for wild birds. *Ecology and Evolution* 8: 7151–7163. doi:10.1002/ece3.4240.

Raven, P. H., J. M. Chase, and J. C. Pires. 2011. Introduction to special issue on biodiversity1. *American Journal of Botany* 98: 333–335. doi:10.3732/ajb.1100055.

Reed, S. E., and A. M. Merenlender. 2008. Quiet, Nonconsumptive Recreation Reduces Protected Area Effectiveness: Quiet recreation in protected areas. *Conservation Letters* 1: 146–154. doi:10.1111/j.1755-263X.2008.00019.x.

Reichholf, J. H. 2001. Störungsökologie: Ursache und Wirkung von Störungen. Bayerische Akademie für Naturschutz und Landschaftspflege (ANL).

Riffell, S. K., K. J. Gutzwiller, and S. H. Anderson. 1996. Does Repeated Human Intrusion Cause Cumulative Declines in Avian Richness and Abundance? *Ecological Applications* 6: 492–505. doi:10.2307/2269386.

Roberts, H., B. Resch, J. Sadler, L. Chapman, A. Petutschnig, and S. Zimmer. 2018. Investigating the Emotional Responses of Individuals to Urban Green Space Using Twitter Data: A Critical Comparison of Three Different Methods of Sentiment Analysis. *Urban Planning* 3: 21–33. doi:10.17645/up.v3i1.1231.

Rogala, J. K., M. Hebblewhite, J. Whittington, C. A. White, J. Coleshill, and M. Musiani. 2011. Human Activity Differentially Redistributes Large Mammals in the Canadian Rockies National Parks. *Ecology and Society* 16: art16. doi:10.5751/ES-04251-160316.

Rosenberg, K. V., A. M. Dokter, P. J. Blancher, J. R. Sauer, A. C. Smith, P. A. Smith, J. C. Stanton, A. Panjabi, et al. 2019. Decline of the North American avifauna. *Science* 366: 120–124. doi:10.1126/science.aaw1313.

Rossi, S. D., J. A. Byrne, and C. M. Pickering. 2015. The role of distance in peri-urban national park use: Who visits them and how far do they travel? *Applied Geography* 63: 77–88. doi:10.1016/j.apgeog.2015.06.008.

Ruddiman, W. F. 2003. The Anthropogenic Greenhouse Era Began Thousands of Years Ago. *Climatic Change* 61: 261–293. doi:10.1023/B:CLIM.0000004577.17928.fa.

Schafft, M., B. Wegner, N. Meyer, C. Wolter, and R. Arlinghaus. 2021. Ecological impacts of water-based recreational activities on freshwater ecosystems: a global meta-analysis. *Proceedings of the Royal Society B: Biological Sciences* 288: 20211623. doi:10.1098/rspb.2021.1623.

Schlemmer, P., M. Barth, and M. Schnitzer. 2020. Comparing motivational patterns of e-mountain bike and common mountain bike tourists. *Current Issues in Tourism* 23: 1186–1190. doi:10.1080/13683500.2019.1606168.

Schorr, M. 2000. Störungsökologische Wirkungen von Bootsportaktivitäten auf Fließgewässer-Libellen - dargestellt am Beispiel der Wieslauter (Pfälzerwald, Rheinland-Pfalz. *Fauna Flora Rheinland-Pfalz* 9: 663–679.

Schwartz, R., and N. Hochmann. 2014. The social media life of public spaces: Reading places through the lens of geo-tagged data. In *Locative Media*, 1st ed., 14. Routledge.

Secondi, J., A. Davranche, M. Théry, N. Mondy, and T. Lengagne. 2020. Assessing the effects of artificial light at night on biodiversity across latitude – Current knowledge gaps. Edited by Nick Isaac. *Global Ecology and Biogeography* 29: 404–419. doi:10.1111/geb.13037.

Smith, V. K., and Y. Kaoru. 1990. What have we learned since hotelling's letter? *Economics Letters* 32: 267–272. doi:10.1016/0165-1765(90)90110-M.

Stålhammar, S., and E. Pedersen. 2017. Recreational cultural ecosystem services: How do people describe the value? *Ecosystem Services* 26: 1–9. doi:10.1016/j.ecoser.2017.05.010.

Stasko, A. D., T. Patenaude, A. L. Strecker, and S. E. Arnott. 2012. Portage connectivity does not predict establishment success of canoe-mediated dispersal for crustacean zooplankton. *Aquatic Ecology* 46: 9–24. doi:10.1007/s10452-011-9378-4.

Steinbauer, M. J., A. Gohlke, C. Mahler, A. Schmiedinger, and C. Beierkuhnlein. 2013. Quantification of wall surface heterogeneity and its influence on species diversity at medieval castles – implications for the environmentally friendly preservation of cultural heritage. *Journal of Cultural Heritage* 14: 219–228. doi:10.1016/j.culher.2012.06.003.

Steven, R., and J. G. Castley. 2013. Tourism as a threat to critically endangered and endangered birds: global patterns and trends in conservation hotspots. *Biodiversity and Conservation* 22: 1063–1082. doi:10.1007/s10531-013-0470-z.

Stinson, J. 2017. Re-creating Wilderness 2.0: Or getting back to work in a virtual nature. *Geoforum* 79: 174–187. doi:10.1016/j.geoforum.2016.09.002.

Stott, T. 2019. Water Sports and Water-Based Recreation. In *Outdoor Recreation*, D. Huddart and T. Stott, 331–359. Cham: Springer International Publishing. doi:10.1007/978-3-319-97758-4_13.

Strava, Inc. Strava. Strava Inc.

Suri, J., P. M. Anderson, T. Charles-Dominique, E. Hellard, and G. S. Cumming. 2017. More than just a corridor: A suburban river catchment enhances bird functional diversity. *Landscape and Urban Planning* 157: 331–342. doi:10.1016/j.landurbplan.2016.07.013.

Tablado, Z., and L. Jenni. 2017. Determinants of uncertainty in wildlife responses to human disturbance: Modulators of wildlife response to recreation. *Biological Reviews* 92: 216–233. doi:10.1111/brv.12224.

Teyssèdre, A., and D. Couvet. 2007. Expected impact of agriculture expansion on the world avifauna. *Comptes Rendus Biologies* 330: 247–254. doi:https://doi.org/10.1016/j.crvi.2007.01.003.

Türk, S., E. Jakob, A. Krämer, and R. Roth. 2004. Outdoor recreation activities in nature protection areas – situation in Germany. In , 2:171–177. Working Papers of the Finnish Forest Research Institute.

United Nations, Departments of Economic and Social Affairs, Population Division. 2019. *World population prospects 2019: highlights*. New York: United Nations.

Urban, M. C. 2015. Accelerating extinction risk from climate change. *Science* 348: 571–573. doi:10.1126/science.aaa4984.

Urlus, J., D. McCutcheon, D. Gilmore, and J. McMahon. 2014. The effect of camera trap type on the probability of detecting different size classes of Australian mammals. In *Camera trapping: Wildlife management and research*, 111–122. Melbourne, Vic., Australia: CSIRO Publishing.

Vaske, J. J., M. P. Donnelly, K. Wittmann, and S. Laidlaw. 1995. Interpersonal versus social-values conflict. *Leisure Sciences* 17: 205–222. doi:10.1080/01490409509513257.

VG Bayreuth. 2009. *B 2 K 09.554*. VG Bayreuth.

Vitousek, P. M., H. A. Mooney, J. Lubchenco, and J. M. Melillo. 1997. Human Domination of Earth’s Ecosystems. *Science* 277: 494–499. doi:10.1126/science.277.5325.494.

Vittersø, J., R. Chipeniuk, M. Skår, and O. I. Vistad. 2004. Recreational Conflict Is Affective: The Case of Cross-Country Skiers and Snowmobiles. *Leisure Sciences* 26: 227–243. doi:10.1080/01490400490461378.

Wilson, R. P., and C. R. McMahon. 2006. Measuring devices on wild animals: what constitutes acceptable practice? *Frontiers in Ecology and the Environment* 4: 147–154. doi:10.1890/1540-9295(2006)004[0147:MDOWAW]2.0.CO;2.

Wist, B., C. Stolter, and K. H. Dausmann. 2022. Sugar addicted in the city: impact of urbanisation on food choice and diet composition of the Eurasian red squirrel (*Sciurus vulgaris*). *Journal of Urban Ecology* 8: juac012. doi:10.1093/jue/juac012.

Wohlgemuth, T., A. Jentsch, and R. Seidl, ed. 2019. *Störungsökologie*. 1st ed. Stuttgart, Deutschland: utb GmbH. doi:10.36198/9783838550183.

Wolf, I. D., G. Hagenloh, and D. B. Croft. 2012a. Visitor monitoring along roads and hiking trails: How to determine usage levels in tourist sites. *Tourism Management* 33: 16–28. doi:10.1016/j.tourman.2011.01.019.

Wolf, I. D., G. Hagenloh, and D. B. Croft. 2012b. Visitor monitoring along roads and hiking trails: How to determine usage levels in tourist sites. *Tourism Management* 33: 16–28. doi:10.1016/j.tourman.2011.01.019.

Wolf, I. D. F. G. 2009. Towards sustainable tourism in outback Australia: the behaviour and impact of nature-based tourists on vegetation and selected wildlife species. UNSW Sydney. doi:10.26190/UNSWORKS/22848.

Zauner, G., and C. Ratschan. 2004. Auswirkungen des Kanusports auf die Fischfauna. Studie im Auftrag des Deutschen Kanuverbandes e. V.

Zink, J., F. Porst, F. Leibl, and M. Heurich. 2022. Digitalisierung in Erholungsnutzung und Outdoorsport als Herausforderung - Auf dem Weg zu einem digitalen Besuchermanagement in Schutzgebieten. *Naturschutz und Landschaftsplanung (NuL)* 54: 20–29. doi:10.1399/NuL.2022.07.02.

Manuscripts

List of manuscripts included in this dissertation & declarations of contributions

This dissertation is cummulative, consisting of five manuskripts, which I collaborated on with colleagues. A detailed break-down of my specific contributions to each manuscript can be found below. For brevity, in the body of this dissertation first person singular is used throughout.

Manuscript 1

Authors: Schweizer A.-M., Leiderer A., Mitterwallner V., Walentowitz A., Mathes G. H., & Steinbauer M. J.

Title: **Outdoor cycling activity affected by COVID-19 related epidemic-control-decisions**

Journal and status: ***PLoS ONE*** 16(5): e0249268 (2021)

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Own contribution: Conceptualization 40%, Data acquisition 40%, Data analysis & figures 20%, Writing – Original Draft 90%, Writing – Review & Editing: 40%, Project administration 90%, corresponding author

Manuscript 2

Authors: Schweizer A.-M., Höschler L., & Steinbauer M. J.

Title: **The Physical Damage of Climbing Activity on Sandstone Lichen Cover**

Journal and status: ***Sustainability***, 13, 13590 (221)

https://doi.org/10.3390/su132413590

Own contribution Conceptualization 40 %, Data acquisition 5%, Data analysis & figures 40%, Writing – Original Draft 80%, Writing – Review & Editing: 80%, Project administration 90%, corresponding author

Manuscript 3

Authors: Schweizer A.-M., Schulte C., Steinbauer M.J.

Title: **The influence of recreational activities on temporal feeding patterns of the common kingfisher (*Alcedo atthis*)**

Journal and status: submitted to Animal Conservation (manuscript ID ACV-10-24-OMR-265)

Own contribution: Conceptualization 40%, Data acquisition 10%, Data analysis & figures 70%, Writing – Original Draft 80%, Writing – Review & Editing: 90%, Project administration 90%

Manuscript 4

Authors: Schweizer A.-M., Schweizer J., Steinbauer M.J.

Title: **Overcoming the challenge of remotely monitoring small birds using video traps and artificial intelligence: An example with the common kingfisher *Alcedo atthis***

Journal and status: submitted to AI & Society (manuscript ID f7d153dd-dadd-4f7b-b366-ae4b1a997353)

Own contribution: Conceptualization 40%, Data acquisition 100%, Data analysis & figures 40%, Writing – Original Draft 90%, Writing – Review & Editing: 90%, Project administration 90%, corresponding author

Manuscript 5

Authors: Schweizer A.-M., Schuster S., Steinbauer M.J.

Title: **Effects of paddle strokes on hatching rates of river trout *Salmo trutta fario***

Journal and status: submitted to Fisheries Oceanography (manuscript ID FOG-24-2061)

Own contribution: Conceptualization 70%, Data acquisition 100%, Data analysis & figures 90%, Writing – Original Draft 90%, Writing – Review & Editing: 90%, Project administration 90%, corresponding author

Manuscript 1 - Outdoor cycling activity affected by COVID-19 related epidemic-control-decisions

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Abstract

Aim: The lockdown of sports infrastructure due to the COVID-19 pandemic has substantially shifted people’s physical activity towards public green spaces. With Germany’s lockdown as one of the more severe governmentally imposed epidemic-control-decisions, we tested to what extent the frequency of outdoor cycling activities changed from March to June 2020.

Methods: User behaviour and frequency in 15 urban and 7 rural German public green spaces was quantified using cycling data from the fitness application Strava. Changes in cycling activities were analysed with four different generalised linear models, correcting for factors like weather conditions and temporal changes in the user base of the fitness application.

Results: We found a clear increase in outdoor cycling sport activities in urban public green spaces in response to epidemic-control decisions (e.g. increase by 81% in April relative to the expected value (95% CI [48%, 110%])). In contrast, biking in rural areas showed no significant change with epidemic-control-decisions in place.

Conclusion: Fitness App data, e.g. from Strava, can be used to monitor visitor behaviour and frequency. The increase in outdoor cycling activities during epidemic control decisions likely reflects a shift of sport activities from indoor and team sports to outdoor and individual sports. This highlights the importance of accessible green space for maintaining physical fitness and health. Beyond this shift, it is likely that outdoor activities may be of particularly importance for stress relief in times of crisis such as the current COVID-19 pandemic.

Introduction

In many countries of the world, governments issued epidemic-control-decisions at the beginning of 2020 to prevent the spreading and transmission of the highly contagious virus

SARS-CoV-2. This novel virus causes COVID-19, a respiratory disease that can cause a variety of health issues (Robert-Koch-Institut 2020) and can lead to death. The measures taken differed between countries and, in countries like Germany, even between federal states but with the joined aim of slowing down the spread of the virus. The results were immense constraints for the private life of citizens, leading to extensive changes in mobility, purchasing behaviour and environmental impact of whole populations (Muhammad et al. 2020, Venter et al. 2020). Facing rising case counts, the German Government issued progressively stricter policies. From March 12th 2020 on, events with an expected attendance of 1,000 people were prohibited (Bundesregierung 2020) and since March 16th, recreational facilities were closed to the public (Presse- und Informationsamt der Bundesregierung 2020), including all tourism related facilities. On March 22nd, social distancing was enacted. The lockdown of sports infrastructure has substantially reduced the possibilities for leisure physical activity and shifted people's physical activity outdoors towards public green spaces. An increase of outdoor recreational activities by almost 300% during mobility confinements, compared to a 3-year average, was shown in Oslo, Norway (Venter et al. 2020). In Germany, similar effects are indicated by search query data from Google Trends (Google Trends 2020) in terms of outdoor recreation key words like "Fahrrad" (bicycle) or "Wandern" (hiking). For those terms, search query in May 2020 were 40% higher than the average of the last 3 years. Trail remoteness and closed canopy cover were identified as important traits for trail selection during the crisis (Venter et al. 2020), suggesting that public green spaces facilitated social distancing and indirectly mitigated the spread of SARS-CoV-2 virus.

Understanding these changes in spatio-temporal patterns of physical activity is important, as there are strong indications that outdoor activities in public green spaces like forests and parks are a major strategy for coping with COVID-19 and the associated epidemic-control decisions (Venter et al. 2020, Egeter et al. 2020, Samuelsson et al. 2020). With group sport activities prohibited, people may feel restricted to sedentary indoor activities, resulting in a potential reduction in physical exercise and increased sitting associated with a higher risk of chronic diseases or worsening physical constitution (Owen et al. 2010, Ammar et al. 2020, Barkles et al. 2020, López-Bueno et al. 2020, Mever et al. 2020). As preventive measure, it is recommended to exercise during lockdown, either at home or outdoors (Chen et al. 2020). The risk of contracting COVID-19 does not decrease when exercising, but a healthy and fit body may handle an infection more successfully (Bloch et al. 2020). Recreational outdoor activities have been proven beneficial not only for physical but also for mental health (Kahlmeier et al. 2017), whereas green environments are more important for mental health benefits than urban grey environments (Fong et al. 2017). Increased greenness is associated with stress reduction (Bowler et al. 2010), lower likelihood of psychological distress and other positive mental health outcomes, especially with physical activity as a mediator for stress reduction (Engemann et al. 2019, Hartig et al. 2014). This indicates that access to public green spaces also enhances the resilience of individuals to cope with crises like a pandemic (Samuelsson et al. 2020).

Over the last years, physical activity is increasingly supported by various fitness applications (short: fitness apps) and the user base of such is growing rapidly (Ang 2020). With the help of a smartphone or other GPS devices, anyone can track their geographical data and upload it to online platforms like social media or fitness apps. These voluntarily offered data have great potential as useful management tools by providing spatio-temporal information (e.g. Norman & Pickering 2019). An app can act as an indicator for visitor figures in nature parks and urban green areas (Hamstead et al. 2018, Levin et al. 2015, Mota & Pickering 2012, Walden-Schreiner et al. 2018, Wood et al. 2013) and thus provide solid data for quantifying frequencies of outdoor sport activities such as cycling, running, or hiking.

In this study, we quantify the effects of governmental epidemic-control-decisions on outdoor cycling activities in Germany. For this, we use publicly available data of cycling behaviour from Strava (Strava Inc.), a popular fitness tracking app. Germany's regulations for social distancing got progressively stricter since the beginning of March 2020 (Presse- und Informationsamt der Bundesregierung 2020), although measures, and their moment of implementation, differed between federal states. With indoor sport facilities closed and group sports prohibited, we expect an immediate increase in outdoor cycling activities with the implementation of epidemic-control-decisions. We further test if observed changes differ between public green spaces in densely populated areas (major cities), and less accessible, but greener countryside locations (nature parks). Results can support the use of data from fitness apps for management purposes.

Methods

General procedure

Systematic changes in the frequency of outdoor cycling activities were analysed using publicly available data from the fitness app Strava (Strava Inc.), which aims to support sportspeople during physical activity. The GPS-trail of users is broken down by Strava into snippets, called segments, oftentimes describing one specific activity like climbing or descending. The Strava app was first released in 2009 and by now has built up a substantial user base. Users of the Strava fitness app can compare their latest performance with their past performances and the performance of other users. Globally, user numbers are constantly rising with 8.2 million in March 2015 (Slavonia 2020) and reaching up to 42 million in July 2019 (Haden 2019). The current accession rate is 1 million new users every 30 days (Strava Inc. 2020). When using this data to quantify changes in spatiotemporal patterns of sport activities, one needs to control for the constantly growing user base and consider possible influential factors like weather conditions. For each analysed segment, we thus aggregated available cycling data per month and quantified their dependence on monthly sunshine hours as well as their increase with time for the respective months. Resulting models were used to predict the expected cycling activities for the respective segment without a lockdown situation and were subsequently compared to the recorded values. We excluded months of winter due to infrequent sports activity and truncated the data to start in 2012, as the app was used too infrequently beforehand to support reliable analyses.

Study areas and sample period

Germany is undergoing a long-term process of urbanization, resulting in 30% of the German population living in large cities by 2015 (Bundesinstitut für Bau, Stadt- und Raumforschung 2020). We chose to conduct this study using data from the 15 largest German cities in terms of population and 7 randomly chosen German nature parks to contrast user frequencies of urban and rural public green spaces (see Table 1 and 2 for additional information). Although most epidemic-control-decisions were issued in March 2020, we consider April, May, and June 2020 to be most influenced by them, due to people adjusting to the new policies. Springtime starts with March and April in Germany, which was marked in 2020 by persisting fair weather (National Centers for Environmental Information 2020).

Table 1. Overview of sampled nature parks. Area figures as reported on the website Naturparke.de (Verband deutscher Naturparke e.V. 2020)

Nature park	Federate state	Area [km2] (2020)
Bavarian Forest	Bavaria	2780
Black Forest	Baden-Wurttemberg	3750
Harz (Lower Saxony)	Lower Saxony	2810
Hohe Mark	North Rhine-Westphalia	1978
Lüneburger Heath	Lower Saxony	1070
Teutoburg Forest/Egge Hills	North Rhine-Westphalia	2736
Usedom Island	Mecklenburg-Western Pomerania	632

Table 2. Overview of sampled cities**.** Area and population figures as reported by the Federal Bureau of Statistics (Statistisches Bundesamt 2020), with area figures rounded mathematically.

City	Federate state	Area [km2] (2016)	Population (2019)
Berlin	Berlin	894	3 669 491
Bremen	Bremen	524	567 559
Cologne	North Rhine-Westphalia	405	1 087 863
Dortmund	North Rhine-Westphalia	281	588 250
Dresden	Saxony	328	556 058
Duisburg	North Rhine-Westphalia	233	498 686
Dusseldorf	North Rhine-Westphalia	217	621 877

Essen	Lower Saxony	210	582 760
Frankfurt am Main	Hesse	248	763 380
Hamburg	Hamburg	755	1 847 253
Hannover	Lower Saxony	204	536 925
Leipzig	Saxony	298	593 145
Munich	Bavaria	311	1 484 226
Nuremberg	Bavaria	186	518, 70
Stuttgart	Baden-Wurttemberg	207	635 911

Data acquisition

We only analysed segments registering the highest user numbers per focal area, as suggested by Norman & Pickering (2019). In Germany, the most popular individual sport activities are cycling and running (Alfs, 2014). Since the data on running segments in rural areas and nature parks is too sparse to be used, we concentrated our efforts on cycling segments. For each sample city, we chose and downloaded two cycling segments, resulting in 30 examined urban segments. We only selected segments with high user frequency with more than 1500 attempts and more than 350 users reporting an attempt. Other requirements were for the segment to pass alongside or cross a body of water or park to qualify it as a green space, to have a minimum length of 500 meters and a comparable mean count of attempts per user. This way, we excluded commuting activities from our analysis. Furthermore, we excluded segments used for any kind of event, e.g. a city run. The seven focal rural areas were selected at random from all 104 German nature parks (Verband deutscher Naturparke e.V. 2020). For each rural area, two cycling segments were chosen, meeting the same requirements as for segments in urban areas, although requirements concerning user frequency had to be reduced to include segments with more than 600 attempts and more than 200 users reporting an attempt. User frequency in nature parks was generally lower due to their distance to highly populated areas and their overall bigger total area. We downloaded data from Strava (Strava Inc.) in June and July 2020, and cleaned data by excluding duplicates, resulting in 3499 data points overall. To correct for the effect that sunshine hours influence individual's exercising behaviour (Tin Tin et al. 2012, Thomas et al. 2009), we identified the closest weather station to focal segments from the German weather service DWD (Deutscher Wetterdienst) and aggregated the number of sunshine hours per month for the period investigated.

Data analysis

We implemented generalised linear models with Poisson family error to quantify the general increase in cycling activities. Models were trained individually for each segment and month, based on data from preceding years without COVID-19 influence, incorporating the continuously growing user base of the fitness application, as well as accounting for the effect of changing weather conditions. Models were implemented with four alternative settings: (A) only including the development of occurrences of sport activities with time [cycling activity ~ year], (B) adding the effect of sunshine hours [cycling activity ~ year + sunshine hours] and (C) additionally including the interaction between sunshine hours and time [cycling activity ~ year + sunshine hours + year : sunshine hours]. A (D) Null Model was also implemented. We discerned the best fitting model using Akaike's Information Criterion (Sakamoto et al. 1986).

Since the data was not normally distributed, the user frequency, as predicted by the model without COVID-19 influence, was compared to the actual user frequencies extracted from Strava (Stava Inc.) via non-parametric bootstrapping. 95% Confidence Intervals were then calculated using the adjusted bootstrap percentile (BCa) method (DiCiccio et al. 1996). This approach was implemented for the months with COVID-19 influence (March – June 2020), to quantify the effect of epidemic-control-decisions as well as for other months (July – October 2019). That way, the approach was validated to predict realistic values when COVID-19 and epidemic-control-decisions were not present. This means the difference between expected and measured activities for March - June 2020 can be attributed to COVID-19 related changes.

We used R version 3.6.2 for all data analysis, including the packages boot (Canty & Ripley 2019, Davidson & K´HInkley 1997), flextable (Gohel 2020a), here (Müller 2017), lubridate (Grolemund & Wickham 2011), MuMIn (Barton 2020), officer (Gohel 2020b), readxl (Wickham & Bryan 2019) and tidyverse (Wickham et al. 2019). For creating the map in Fig 1 we used ciTools (Hamman & Avery2020), gridBase (Murrell 2014), Lattice (Deepayan 2008) and raster (Hijmans 2020).

Results

The best fitting model was discerned to be Model A, using Akaike's Information Criterion. Henceforth we will focus primarily on Model A, which describes the development of occurrences of sport activities over time, and performs best in 69% of cases. With epidemic-control-decisions in place (March – June 2020), we see a significant increase of 55% (95% CI [45%, 74%]) cycling activity in urban public green spaces. In contrast, rural public green spaces show no significant differences. During times without the influence of epidemic-control-decisions (July – October 2019), all three models show either no significant cycling frequency or slightly overestimate cycling frequency in urban and rural public green spaces (see Fig 2). Our models show a significant increase of up to 81% in cycling activity in urban public green spaces (e.g. Model A, April: med. diff. = 54.4, percent diff. = 81%, 95% CI [48%, 110%]). For a detailed visualization of every sampling site see Fig 1.

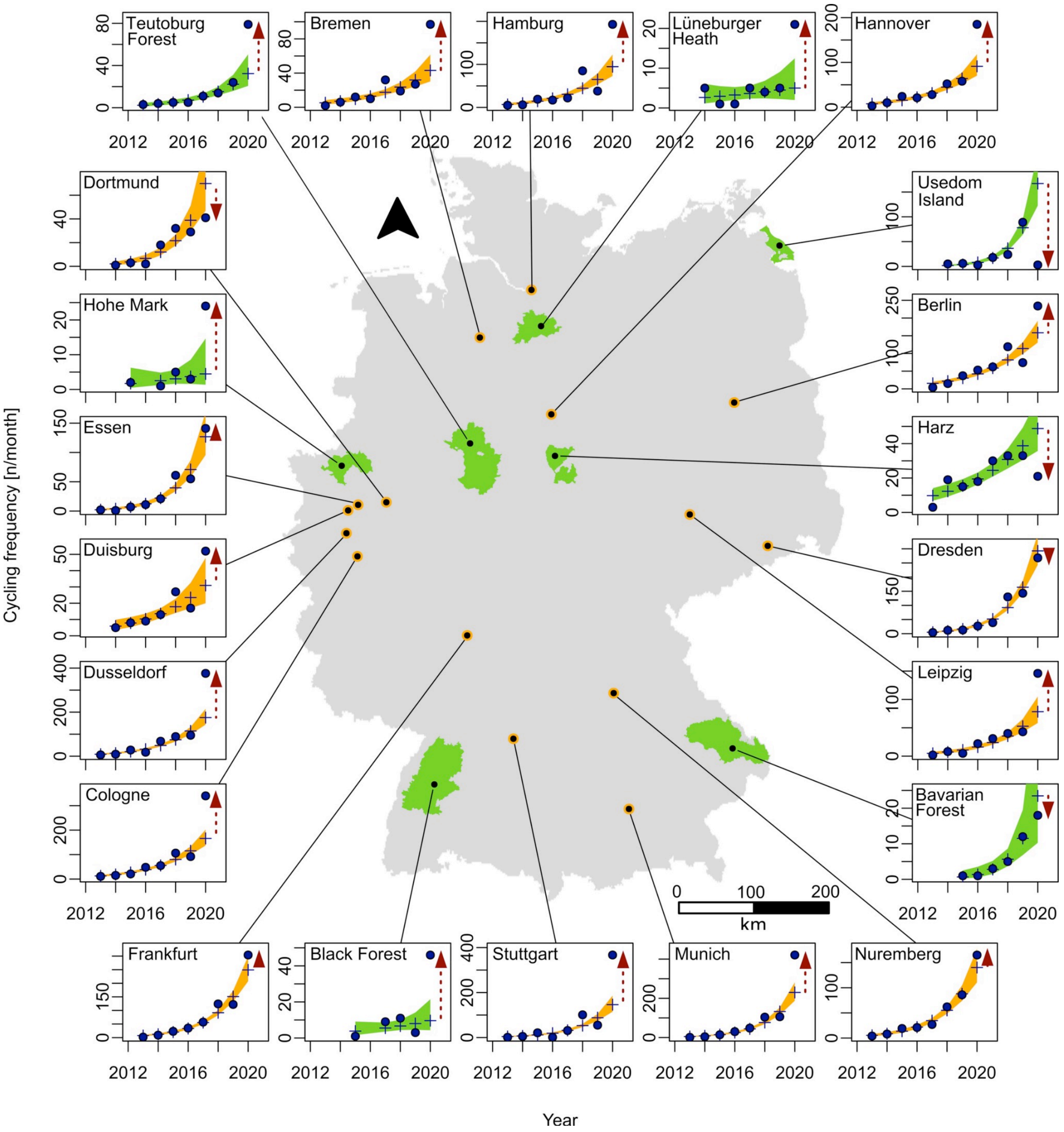

Figure 1. Map of study sites and respective cycling frequency. Cycling frequency displayed as measured (point) and predicted (plus, Modell A with user numbers as factor) values for the month April for all urban (orange) and rural (green) sample sites. The red dashed arrows indicates a Covid-19 related difference and the direction of change in user frequency. The background shows the outlines of Germany with the locations of focal cities and nature parks (Bundesamt für Naturschutz 2020).

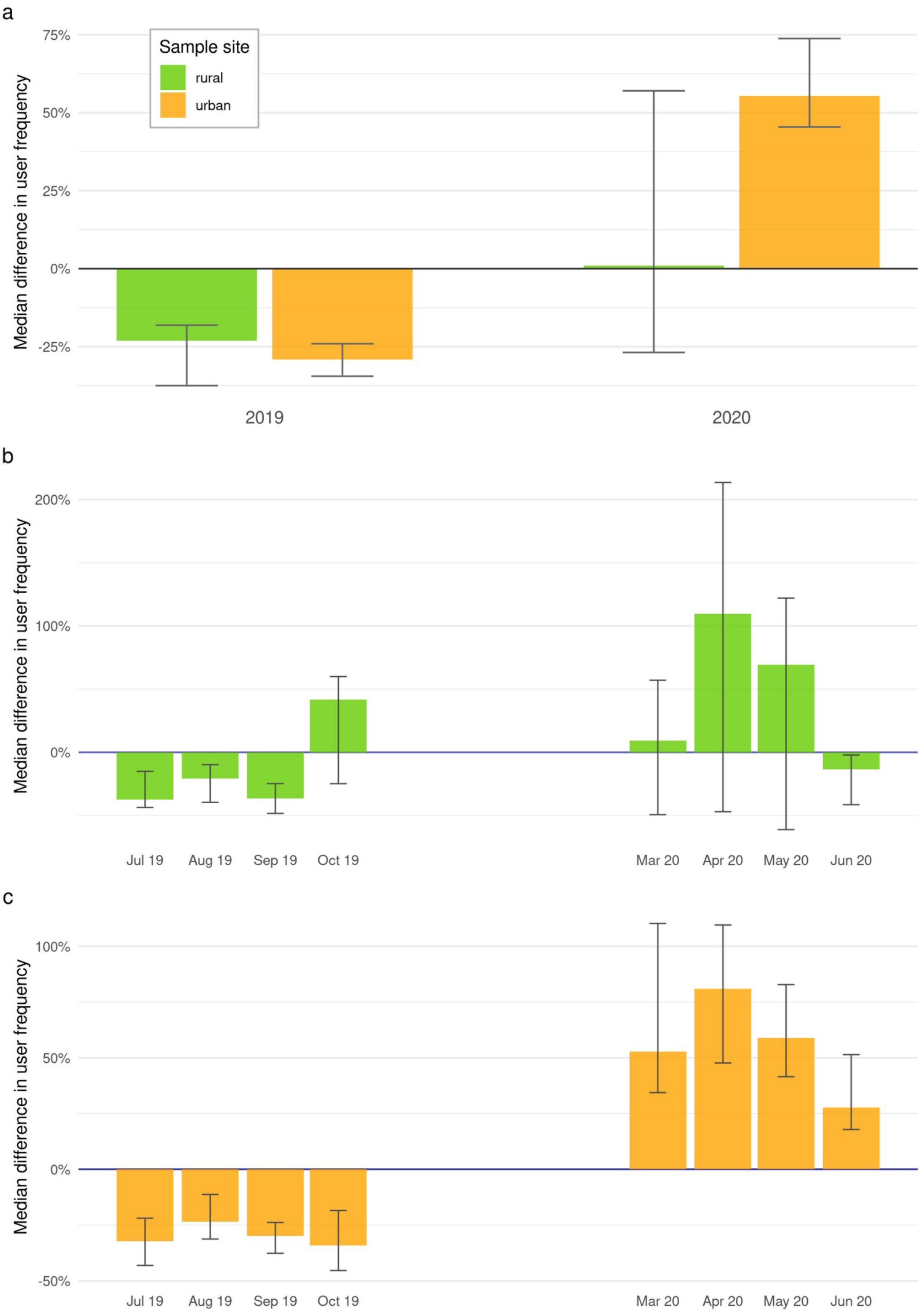

Figure 2. Comparison of urban and rural cycling behaviour. Graphic a displays a summary of Model A [cycling activity ~ year]. The plot shows the median differences in user frequency, detected in rural (green) and urban (yellow) public green spaces in times with influence of epidemic-control-decisions (2020) and without (2019). Bars indicate mean difference, whiskers show 95% Confidence Intervals. Graphic b and c display median differences in user frequency, calculated by Modell A [cycling activity ~ year]. Graphic b shows results for rural and Graphic c for urban public green spaces in months with influence of epidemic-control-decisions (March – June 2020) and without (July – October 2019).

Discussion

In this study, we showed that epidemic-control-decisions in Germany in response to the COVID-19 pandemic have caused a rise in cycling activity in urban areas, reflected by user frequencies of the Strava fitness app (Strava Inc.). Our findings align with augmented sales of bicycles and biking equipment during the COVID-19 pandemic, going up 9.2% in Germany alone (Eisenberger 2020). The effects differed between urban and rural public green spaces, whereby rural areas registered no significant change in user frequency with epidemic-control-decisions in place (March – June 2020) (see Fig 2a-c). Urban areas, however, show a general increase of 55% in cycling activity, with a maximum increase of 81% per month. Similar effects were found in Oslo, Norway, where outdoor recreational activity during mobility confinement increased by 300% (Venter et al 2020). The Google Mobility Report of May 2020 for Germany (Google LLC 2020) states that visitor frequency for public green spaces, including national parks, public beaches, marinas, dog parks, plazas and public gardens, have gone up by 225%. It is to be expected that easy to access public green spaces designed for tourism, including beaches and public gardens, will have higher activity fluctuations than regular public green spaces, which were used in this study. Although our numbers turn out lower compared to similar studies, we observe the same effect.

Looking at other studies, there is evidence of increased sitting due to governmental epidemic-control-decisions (Barkley et al. 2020, Meyer et al. 2020). However, the effects upon physical activity are not uniform, with some individuals decreasing their physical activity while others increased their activity. It is possible that those who increased their physical activity were individuals who successfully transitioned from gyms and recreation centers to urban green spaces.

The increase in outdoor activities is a direct result of the prohibition of team sports and closed sports infrastructure, which prevent most indoor sport activities. It may also reflect the larger amount of available free time, resulting from the rising count of people working reduced hours (Wichert 2020). Their number increased dramatically by over seventeen thousand percent (17 447%) from 43 000 affected people in January to 7 502 265 in April (Bunesagentur für Arbeit 2020). We suspect that the rise in user frequency in urban public green spaces observed in this study is pronounced, in comparison with rural public green spaces, because of high urban population density and less available green space per individual. While a shift to outdoor sport may be important to maintain physical activity with epidemic-control decisions in place, outdoor sports also facilitate psychological welfare (Bowler et al. 2010), which is of similar importance for a population, especially during a pandemic such as COVID-19. The COVID-19 pandemic, and the resulting epidemic-control-decisions, have added stressors to people's daily life. The initial lack of information about the novel SARS-CoV-2 virus, followed by a plethora of different epidemic-control-decisions, might have unsettled the public. The closing of educational facilities for a limited time resulted in teaching arrangements varying majorly between facilities. Legal guardians and students alike had trouble to adapt to these drastically different teaching arrangements, mostly because of lacking communication with school staff

(Porsch & Porsch 2020). According to a non-representative study (Lerch 2020), most legal guardians were facing a huge dual burden of working from home and supervising their offspring's home-schooling, let alone minding household chores. Social distancing and the temporary closing of businesses and facilities caused people to be restricted to their own home. The closing of sports facilities implies that all 27.6 million members of German sport clubs (Deutscher Olympischer Sportbund e.V. 2019) are no longer able to exercise in the weekly training sessions. Furthermore, the 11.7 million members of the German gyms (Sholeh 2020) are forced to either skip their training or find new ways of being physically active. At times, people were only allowed outside alone or in small groups when shopping for essentials or when exercising. Social gatherings of all kinds had to be cancelled, leading to a disrupted and reduced social life. These policies also led to a surge in domestic violence (Bayer 2020, Hecht 2020), although its extend will only become clear with next year's criminal statistics. Lastly, people might have felt afraid for themselves or their loved ones contracting COVID-19, have had to deal with being infected or with bereavement. The demand for mental health consultations has been on the rise (Kang et al. 2020), with counsellors trying to relief patient's worries and stress. All these stressors of people being restricted to their own homes, coping with completely new challenges concerning employment, care work, domestic work and social life, had to be compensated. Our data, along with Venter et al. (Venter et al. 2020), suggests that for stress relief, people turned to individual outdoor sport activities like cycling, using available public green spaces at a higher rate than before the COVID-19 pandemic.

Consequences for city planning

Since a surge in outdoor activities was only observed in urban public green spaces, they seem to be more crucial for short-term stress relief than rural public green spaces, presumably due to high population density in cities. A recent study [66] found an increase in public green spaces in major cities by 3.2% since 1996. Currently, public green spaces make up 10.9% of major German cities, which is above the national average of 6%. Although less urbanized and rural areas have less public green spaces inside city borders on a percental basis, green spaces situated outside of city limits are much more accessible. These vast rural and natural green spaces lead to a much more relaxed resident-to-green-space ratio in rural areas compared to urban areas. Additionally, epidemic-control-decisions have led to a steep decline in national and international tourism (Presse- und Informationsamt der Budesregierung 2020) and in turn to lower visitor frequencies of nature parks. Advantages of green spaces are numerous. While promoting mental and physical health (Kahlrmeier et al. 2017), they also absorb CO2, provide shade, buffer noise with greenery and provide refuge for wild species (Miller 2005). Since people seem to actively seek out green spaces for their stress relieving properties, these areas mitigate the spread of COVID-19 and promote social distancing. Future city planning should continue to establish numerous, accessible urban public green spaces to stabilize the mental and physical well-being of the population, to improve the populations resilience and to provide opportunity for stress relief.

Methodological aspects and the potential of fitness applications

For our analysis, we build four models with different settings. Model A models the development of occurrences of sport activities over time. Model B added the effect of sunshine hours, a factor that is proven to influence outdoor activity (Tin Tin et al. 2020, Thomas et al. 2009). Model C included the interaction between sunshine hours and time. We also implemented a Null model (D). Surprisingly, the best fitting model was discerned to be Model A instead of any other model containing the influence of sunshine hours. Rising user numbers, new segments and distribution of active user on segments are currently not in equilibrium and dynamically changing. Thus, these factors explain more variation of the data than sunshine hours. This may change over time when user numbers develop at a steadier rate and users are more evenly distributed throughout urban and rural areas. Since the Strava app (Strava Inc.) does not focus on orientation, user numbers may stay low in rural areas compared to urban areas. It is important to orientate oneself, especially in rural areas where users are potentially alone and cannot ask for directions. To that end, users might utilise other fitness apps.

The results presented in this paper are based on the information provided by one fitness app and thus the changes of outdoor cycling activities during lockdown are only partly reflected, although Strava is one of the most popular and widespread fitness apps in Germany. Behavioural changes of people exercising outdoors without tracking their activities are not captured in our dataset. Furthermore, user shifts between fitness apps are not reflected as our results are only based on Strava data. Nevertheless, our analysis provides valuable insights into activity changes of cyclists with georeferenced user-generated open-access data. The used approach is suitable to assess rapid changes occurring during the sudden oncoming of the global COVID-19 pandemic, which did not allow for stratified planned monitoring.

Some studies have already conducted research with Strava data, although none of them have attempted to predict future developments of user frequencies (Venter et al. 2020, Norman & Pickering 2019). Monitoring user frequency of green spaces can be achieved with the help of fitness apps, as shown in this paper. Via observing current user frequencies and predicting future frequencies, tending plans for green spaces can be compiled. This method will prove very useful for management purposes of urban and rural green spaces.

Strava does not directly provide information concerning the gender distribution of users. However, from Strava's annual report of 2018 (Strava Inc. 2018) it can be concluded from cycling specific upload figures, that the distribution is massively skewed, with most of the users identifying as male (81%). This is in high contrast to the 51% men's quota in recreational cycling in Germany (Purcher & Buehler 2008). Since Strava's main feature is its high score table, the app itself creates a highly competitive setting. In most societies, especially western ones, people identifying as male tend to be more positive about and to seek out competition than people identifying as female (Gneezy et al. 2009, Niederle & Vesterlund 2011), which could explain the uneven gender distribution on the fitness app. Hence, our findings apply to people identifying as male and not to the general public.

Conclusion

Data from fitness apps can indicate user behaviour and frequency in green spaces, as shown using the Strava app. Therefore, fitness apps can be a useful management tool for assessing visitor frequency. In this study, we found evidence that outdoor cycling sport activities increased in urban public green spaces in Germany in response to COVID-19 related epidemic-control decisions.

Statements and Declarations

Competing Interest: The authors have declared that no competing interests exist.

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References

Alfs, C. (2014). *Sportkonsum in Deutschland: Empirische Analysen zur Allokation von Zeit und Geld für Sport*. Springer Gabler. https://doi.org/10.1007/978-3-658-06473-0

Ammar, A., Brach, M., Trabelsi, K., Chtourou, H., Boukhris, O., Masmoudi, L., Bouaziz, B., Bentlage, E., How, D., Ahmed, M., Müller, P., Müller, N., Aloui, A., Hammouda, O., Paineiras-Domingos, L. L., Braakman-Jansen, A., Wrede, C., Bastoni, S., Pernambuco, C. S., … On Behalf of the ECLB-COVID19 Consortium On Behalf of the ECLB-COVID19 Consortium. (2020). Effects of COVID-19 Home Confinement on Eating Behaviour and Physical Activity: Results of the ECLB-COVID19 International Online Survey. *Nutrients*, *12*(6), 1583. https://doi.org/10.3390/nu12061583

Ang, C. (2020, September 10). The Growth of Home Fitness Apps. *Visual Capitalist*. https://www.visualcapitalist.com/the-growth-of-home-fitness-apps-2020/

Barkley, J. E., Lepp, A., Glickman, E., Farnell, G., Wiet, R., & Dowdell, B. (2020). *The Acute Effects of the COVID-19 Pandemic on Physical Activity and Sedentary Behavior in University Students and Employees*. 14.

Barton, K. (2020). *MuMIn: Multi-Model Inference* (R package version 1.43.17) [Computer software].

Bayer, A. (2020). *Häusliche Gewalt in Brandenburg während Lockdown angestiegen*. https://www.rbb24.de/studiofrankfurt/panorama/coronavirus/beitraege_neu/2020/07/corona-gewalt-gegen-frauen-lockerungen-lockdown-partnerschaft-brandenburg-haeuslich-gewalt.html

Bloch, W., Halle, M., & Steinacker, J. (2020). Sport in Zeiten von Corona. *Deutsche Zeitschrift für Sportmedizin*, *71*(4), Article 4. https://doi.org/10.5960/dzsm.2020.432

Bowler, D. E., Buyung-Ali, L. M., Knight, T. M., & Pullin, A. S. (2010). A systematic review of evidence for the added benefits to health of exposure to natural environments. *BMC Public Health*, *10*, Article 1. https://doi.org/10.1186/1471-2458-10-456

Bundesagentur für Arbeit. (n.d.). *Statistik der Bundesagentur für Arbeit*. Retrieved April 26, 2020, from https://statistik.arbeitsagentur.de/

Bundesamt für Naturschutz. (2020). *Naturparke 2020*. BfN, Bonn, Germany.

Bundesinstitut für Bau, Stadt- und Raumforschung. (n.d.). *BBSR - Komponenten der Raumbeobachtung—Städte und Gemeinden*. Retrieved June 4, 2020, from https://www.bbsr.bund.de/BBSR/DE/forschung/raumbeobachtung/Komponenten/VergleichendeStadtbeobachtung/staedte-gemeinden/staedte-gemeinden.html

Bundesregierung. (n.d.). *Besprechung der Bundeskanzlerin mit den Länderchefs*. Bundesregierung. Retrieved May 25, 2020, from https://www.bundesregierung.de/breg-de/themen/coronavirus/beschluss-zu-corona-1730292

Canty, A., & Ripley, B. (2019). *boot: Bootstrap R (S-Plus) Functions.* [Computer software].

Chen, P., Mao, L., Nassis, G. P., Harmer, P., Ainsworth, B. E., & Li, F. (2020). Coronavirus disease (COVID-19): The need to maintain regular physical activity while taking precautions. *Journal of Sport and Health Science*, *9*(2), Article 2. https://doi.org/10.1016/j.jshs.2020.02.001

Davison, A. C., & Hinkley, D. V. (1997). *Bootstrap methods and their application*. Cambridge University Press.

Deepayan, S. (2008). *Lattice: Multivariate Data Visualization with R*. Springer.

Deutscher Olympischer Sportbund e.V. (2020). *Bestandserhebung 2019*. https://cdn.dosb.de/user_upload/www.dosb.de/medien/BE/BE-Heft_2019.pdf

DiCiccio, T. J., Efron, B., Hall, P., Martin, M. A., Canty, A. J., Davison, A. C., Hinkley, D. V., Gleser, L. J., Lee, S. M. S., Young, G. A., DiCiccio, T. J., & Efron, B. (1996). Bootstrap confidence intervalsCommentCommentCommentCommentRejoinder. *Statistical Science*, *11*(3), 189–228. https://doi.org/10.1214/ss/1032280214

Egeter, M., Finger-Stich, A., Karn, S., Ketterer Bonnelame, L., Schellenberger, S., & Siegrist, D. (2020). Bleiben Sie zu Hause. Bitte. Alle. Zwei Befragungen zum Freizeitverhalten der Bevölkerung in Bezug auf Frei- und Grünräume während der Coronakrise in der Schweiz. *Schriftenreihe Des Instituts Für Landschaft Und Freiraum*, *18*.

Eisenberger, D. (2020). *Pressemitteilung—Fahrrad-und E-Bike-Industrie trotzen der Corona-Krise* [News release]. ZIV Zweirad-Industrie-Verband. https://www.ziv-zweirad.de/fileadmin/redakteure/Downloads/PDFs/PM_2020_02.09._Fahrradmarkt_Stimmungsbarometer_1._HJ_2020.pdf

Engemann, K., Pedersen, C. B., Arge, L., Tsirogiannis, C., Mortensen, P. B., & Svenning, J.-C. (2019). Residential green space in childhood is associated with lower risk of psychiatric disorders from adolescence into adulthood. *Proceedings of the National Academy of Sciences*, *116*(11), Article 11. https://doi.org/10.1073/pnas.1807504116

Fong, K. C., Hart, J. E., & James, P. (2018). A Review of Epidemiologic Studies on Greenness and Health: Updated Literature Through 2017. *Current Environmental Health Reports*, *5*, Article 1. https://doi.org/10.1007/s40572-018-0179-y

Gneezy, U., Leonard, K. L., & List, J. A. (2009). Gender Differences in Competition: Evidence\\ From a Matrilineal and a Patriarchal Society. *Econometrica*, *77*(5), Article 5. https://doi.org/10.3982/ECTA6690

Gohel, D. (2020a). *flextable: Functions for Tabular Reporting* [Computer software]. https://CRAN.R-project.org/package=flextable

Gohel, D. (2020b). *officer: Manipulation of Microsoft Word and PowerPoint Document* [Computer software]. https://CRAN.R-project.org/package=officer

Google LLC. (2020). *Google COVID-19 Community Mobility Report* [Mobilitätsbericht]. https://www.google.com/covid19/mobility/

Grolemund, G., & Wickham, H. (2011). *Dates and Times Made Easy with lubridate* [Computer software]. http://www.jstatsoft.org/v40/i03/

Haden, J. (2019, July 17). *Strava Has 42 Million Users and Adds 1 Million More Each Month. Will It Be the Next Great Sports Brand?* Inc.Com. https://www.inc.com/jeff-haden/10-years-in-strava-now-adds-1-million-users-a-month-but-can-it-become-next-great-sports-brand.html

Hamman, J., & Avery, M. (2020). *ciTools: Confidence or Prediction Intervals, Quantiles, and Probabilities for Statistical Models* (R package version 0.5.2) [Computer software].

Hamstead, Z. A., Fisher, D., Ilieva, R. T., Wood, S. A., McPhearson, T., & Kremer, P. (2018). Geolocated social media as a rapid indicator of park visitation and equitable park access. *Computers, Environment and Urban Systems*, *72*, 38–50. https://doi.org/10.1016/j.compenvurbsys.2018.01.007

Hartig, T., Mitchell, R., de Vries, S., & Frumkin, H. (2014). Nature and Health. *Annual Review of Public Health*, *35*(1), Article 1. https://doi.org/10.1146/annurev-publhealth-032013-182443

Hecht, P. (2020). *Häusliche Gewalt und Corona: Eine doppelte Bedrohung*. https://taz.de/Haeusliche-Gewalt-und-Corona/!5682407/

Hijmans, R. J. (2020). *raster: Geographic Data Analysis and Modeling* (R package version 3.3-13) [Computer software].

Kahlmeier, S., Götschi, T., Cavill, N., Brand, C., Fernandez, A. C., Rojay Ruedas, D., Woodcock, J., Kelly, P., Lieb, C., Oja, P., Foster, C., Rutter, H., & Racioppi, F. (2017). *Health economic assessment tool (HEAT) for walking and for cycling*. World Health Organization Regional Office for Europe.

Kang, C., Tong, J., Meng, F., Feng, Q., Ma, H., Shi, C., Yuan, J., Yang, S., Liu, L., Xu, L., Xi, Y., Li, W., Zhao, X., & Yang, J. (2020). The role of mental health services during the COVID-19 outbreak in China. *Asian Journal of Psychiatry*, *52*, 102176. https://doi.org/10.1016/j.ajp.2020.102176

Lerch, I. (2020). *Umfrage bei Eltern: Stress durch Homeschooling*. https://www.ndr.de/nachrichten/info/Corona-Umfrage-Eltern-durch-Kinderbetreuung-gestresst,kinderbetreuung220.html

Levin, N., Kark, S., & Crandall, D. (2015). Where have all the people gone? Enhancing global conservation using night lights and social media. *Ecological Applications*, *25*(8), Article 8. https://doi.org/10.1890/15-0113.1

López-Bueno, R., Calatayud, J., Andersen, L. L., Balsalobre-Fernández, C., Casaña, J., Casajús, J. A., Smith, L., & López-Sánchez, G. F. (2020). Immediate Impact of the COVID-19 Confinement on Physical Activity Levels in Spanish Adults. *Sustainability*, *12*(14), 5708. https://doi.org/10.3390/su12145708

Meyer, J., McDowell, C., Lansing, J., Brower, C., Smith, L., Tully, M., & Herring, M. (2020). *Changes in physical activity and sedentary behaviour due to the COVID-19 outbreak and associations with mental health in 3,052 US adults* [Preprint]. Psychiatry. https://doi.org/10.33774/coe-2020-h0b8g

Miller, J. R. (2005). Biodiversity conservation and the extinction of experience. *Trends in Ecology & Evolution*, *20*(8), Article 8. https://doi.org/10.1016/j.tree.2005.05.013

Mota, V. T. da, & Pickering, C. (2012). *How can we use social media to know more about visitors to natural areas?* (J. Dehez, Ed.).

Muhammad, S., Long, X., & Salman, M. (2020). COVID-19 pandemic and environmental pollution: A blessing in disguise? *Science of The Total Environment*, *728*, 138820. https://doi.org/10.1016/j.scitotenv.2020.138820

Müller, K. (2017). *here: A Simpler Way to Find Your Files* [Computer software]. https://CRAN.R-project.org/package=here

Murrell, P. (2014). *gridBase: Integration of base and grid graphics* (R package version 0.4-7) [Computer software].

National Centers for Environmental Information. (2020, September 30). *State of the Climate | National Centers for Environmental Information (NCEI)*. https://www.ncdc.noaa.gov/sotc/

Niederle, M., & Vesterlund, L. (2011). Gender and Competition. *Annual Review of Economics*, *3*, Article 1. https://doi.org/10.1146/annurev-economics-111809-125122

Norman, P., & Pickering, C. M. (2019). Factors influencing park popularity for mountain bikers, walkers and runners as indicated by social media route data. *Journal of Environmental Management*, *249*, 109413. https://doi.org/10.1016/j.jenvman.2019.109413

Owen, N., Sparling, P. B., Healy, G. N., Dunstan, D. W., & Matthews, C. E. (2010). Sedentary Behavior: Emerging Evidence for a New Health Risk. *Mayo Clinic Proceedings*, *85*(12), Article 12. https://doi.org/10.4065/mcp.2010.0444

Porsch, R., & Porsch, T. (2020). Fernunterricht als Ausnahmesituation. In D. Fickermann & B. Edelstein (Eds.), *„Langsam vermisse ich die Schule ...“* (pp. 61–78). Waxmann Verlag GmbH. https://doi.org/10.31244/9783830992318.03

Presse- und Informationsamt der Bundesregierung (BPA). (n.d.). *Vereinbarung zwischen der Bundesregierung und den Regierungschefinnen und Regierungschefs der Bundesländer angesichts der Corona-Epidemie in Deutschland*. Bundesregierung. Retrieved May 25, 2020, from https://www.bundesregierung.de/breg-de/aktuelles/vereinbarung-zwischen-der-bundesregierung-und-den-regierungschefinnen-und-regierungschefs-der-bundeslaender-angesichts-der-corona-epidemie-in-deutschland-1730934

Pucher, J., & Buehler, R. (2008). Making Cycling Irresistible: Lessons from The Netherlands, Denmark and Germany. *Transport Reviews*, *28*(4), Article 4. https://doi.org/10.1080/01441640701806612

Robert-Koch-Institut RKI (2020). (n.d.). *SARS-CoV-2 Steckbrief zur Coronavirus-Krankheit-2019 (COVID-19)*. https://www.rki.de/DE/Content/InfAZ/N/Neuartiges_Coronavirus/Steckbrief.html

Sakamoto, Y., Ishiguro, M., & Kitagawa, G. (1986). *Akaike information criterion statistics*. KTK Scientific Publishers ; D. Reidel ; Sold and distributed in the U.S.A. and Canada by Kluwer Academic Publishers.

Samuelsson, K., Barthel, S., Colding, J., Macassa, G., & Giusti, M. (2020). *Urban nature as a source of resilience during social distancing amidst the coronavirus pandemic* [Preprint]. Open Science Framework. https://doi.org/10.31219/osf.io/3wx5a

Sholeh. (n.d.). *Deutscher Fitnessmarkt*. Arbeitgeberverband Deutscher Fitness- Und Gesundheits-Anlagen. Retrieved September 16, 2020, from https://dssv.de/presse/statistik/deutscher-fitnessmarkt/

Slavonia, M. (2020, December 5). *Sampling Strava | Mark Slavonia*. http://markslavonia.com/sampling-strava/

Statistisches Bundesamt. (2020a). *25 Quadratmeter Grünanlage stehen Bewohnerinnen und Bewohnern deutscher Metropolen im Schnitt zur Verfügung*. Statistisches Bundesamt. https://www.destatis.de/DE/Presse/Pressemitteilungen/Zahl-der-Woche/2020/PD20_37_p002.html

Statistisches Bundesamt (Destatis). (2020b). *Daten aus dem Gemeindeverzeichnis: Städte in Deutschland nach Fläche, Bevölkerung und Bevölkerungsdichte*. https://www.destatis.de/DE/Themen/Laender-Regionen/Regionales/Gemeindeverzeichnis/Administrativ/05-staedte.html

Strava, Inc. (n.d.). *Strava* [Computer software]. Strava Inc. strava.com

Strava Inc. (2018). *Strava—Das Sportjahr in Zahlen*.

Strava Inc. (2020, April 2). *Strava Milestones: 50 Million Athletes and 3 Billion Activity Uploads*. Strava. https://blog.strava.com/press/strava-milestones-50-million-athletes-and-3-billion-activity-uploads/

Thomas, T., Jaarsma, R., & Tutert, B. (2009). Temporal variations of bicycle demand in the Netherlands: The influence of weather on cycling. *88th TRB Annual Meeting, 11-15 January 2009, Washington DC, USA*, 17.

Tin Tin, S., Woodward, A., Robinson, E., & Ameratunga, S. (2012). Temporal, seasonal and weather effects on cycle volume: An ecological study. *Environmental Health*, *11*(12), Article 12. https://doi.org/10.1186/1476-069X-11-12

Venter, Z. S., Aunan, K., Chowdhury, S., & Lelieveld, J. (2020). COVID-19 lockdowns cause global air pollution declines with implications for public health risk. *Proceedings of the National Academy of Sciences*, *117*(32), Article 32. https://doi.org/DOI: 10.1101/2020.04.10.20060673

Venter, Z. S., Barton, D. N., Gundersen, V., & Figari, H. (2020). Urban nature in a time of crisis: Recreational use of green space increases during the COVID-19 outbreak in Oslo, Norway. *Environmental Research Letters*, *15*(10), Article 10. https://doi.org/10.1088/1748-9326/abb396

Verband Deutscher Naturparke e.V. (2020, July 10). *Naturparke finden: VDN - Verband Deutscher Naturparke e.V.* https://www.naturparke.de/naturparke/naturparke-finden.html?tx_fenatureparks_search%5Bcontroller%5D=Search&cHash=7ff6b89e5efb624f1ebd3a3359a3039b

Walden-Schreiner, C., Rossi, S. D., Barros, A., Pickering, C., & Leung, Y.-F. (2018). Using crowd-sourced photos to assess seasonal patterns of visitor use in mountain-protected areas. *Ambio*, *47*, Article 7. https://doi.org/10.1007/s13280-018-1020-4

Wichert, J. (n.d.). *Definition: Kurzarbeit* [Text]. https://wirtschaftslexikon.gabler.de/definition/kurzarbeit-39815; Springer Fachmedien Wiesbaden GmbH. Retrieved December 9, 2020, from https://wirtschaftslexikon.gabler.de/definition/kurzarbeit-39815/version-263215

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., … Yutani, H. (2019). Welcome to the Tidyverse. *Journal of Open Source Software*, *4*(43), 1686. https://doi.org/10.21105/joss.01686

Wickham, H., & Bryan, J. (2019). *readxl: Read Excel Files* (R package version 1.3.1) [Computer software].

Wood, S. A., Guerry, A. D., Silver, J. M., & Lacayo, M. (2013). Using social media to quantify nature-based tourism and recreation. *Scientific Reports*, *3*, Article 1. https://doi.org/10.1038/srep02976

Manuscript 2 - The Physical Damage of Climbing Activity on Sandstone Lichen Cover

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Abstract

Climbing activities affect cliff site species. With cliff sites harbouring unique species communities, the rise in popularity of outdoor climbing activities is a major threat. In this study, we assessed a previously unclimbed boulder before, during and after 500 climbing ascents. We observed an overall reduction in lichen cover by 4.2–9.5%, located around the footholds and combined foot- and handhold but not the handhold. We found the reduction in lichen cover to be strongest at the very start of the climbing treatment and to lessen over time. Therefore, management should focus on directing climbing activities to selected sites, while protecting sites with high conservation value where climbing is prohibited entirely.

Introduction

Climbing activities affect cliff site species (Tessler & Clark 2016, Lorite et al. 2017, March-salas et al. 2018, Schmera et al. 2018, Strumia et al. 2020). With bouldering, rock climbing and other climbing activities becoming more popular, and with sport climbing being now accepted as an Olympic discipline, the importance of understanding the ecological impact of climbing activities increases. Estimates for 2010 and 2017 indicate an increase from 300,000 to 9,700,000 climbers in the USA [6] and from 300,000 to over 500,000 climbers in Germany (Deutscher Alpenverein e.V. 2020 &2021. Cliff sites are naturally protected by their inaccessibility against common disturbances, e.g., grazing or human activity (Clark & Hessl 2015). They are known to harbour unique species diversity, including rare and endemic taxa (Larson et al. 2000, McMillan & Douglas 2002,Kuntz & Douglas 2006, Bogess et al. 2017). Understanding how environmental damage scales with the number of climbing ascents is one of the central questions for sustainable management of the popular sport in semi-natural settings.

Cliff sites consist of zones, each offering different habitat parameters promoting distinct species communities (Larson et al. 2000). The most abundant organisms at cliff sites are lichen (Holzschuh 2016). They are a symbiotic connection of fungi and photobiotic organisms, such as cyanobacteria or green algae. The fungus provides protection and fixation to the substrate, while the algae provides nutrition via photosynthesis (Honegger 1998). Lichen can grow on substrates with little or no nutrition, such as bare rock. Most lichen are sealing off stone surfaces and thus can prevent erosion (Steinbauer et al. 2013). Lichen can also exudate chemical weathering agents, which facilitate mineral neoformation, e.g., turning rock surfaces into soil Chen et al. 2000). They serve as food for higher order taxa, such as snails, and can be used as an indicator to monitor shifts in cliff ecosystems (Baur et al. 2007). Climbing activity reduces the cover and number of lichen species (Clark & Hessl 2015) and especially lowers the frequency of epilithic lichen (Baur et al. 2007). However, when accounting for abiotic effects, such as slopes and pockets, species numbers can be increased by climbing (Kuntz & Douglas 2006). When affected, lichen are oftentimes scraped off the rock, whereas affected vascular plants suffer mostly non-lethal damages (Kelly & Larson 1997, Nuzzo 1996). Other than lichen, vascular plants are mostly found on soil trapped in crevices or pockets or on plateaus. At climbed sites, they can be damaged by trampling or being used as anchors. Case studies have found that White Cedar trees (*Thuja occidentalis*) show more signs of physical damage (Kelly & Larson 1997) and 35% more flowering ramets of *Solidago sciaphila* break at climbed sites compared to unclimbed sites (Nuzzo 1996). In contrast to lichen and vascular plants, studies generally found that bryophytes are not impacted by climbing activity (Clark & Hessl 2015, Kuntz & Douglas 2006, Baur et al. 2007).

In this study, we investigate how the number of climbing ascents scales with the damage caused to lichen cover. It is possible that climbing activities could be restricted to a sustainable limit. However, if sensitive species already suffer from very few climbing ascents, management strategies may have to direct climbing activities to selected sites while protecting cliff sites where climbing is prohibited entirely. The differences between lichen communities at climbed and unclimbed sites has been shown to increase with rising climbing activity (Boggess et al. 2017). Climbed sites with high visitor numbers show a greater reduction in the abundance and richness of endangered plant species (Lorite et al. 2017). In contrast, moderate bouldering activity in a remote area was not found to threaten vegetation diversity Tessler & Clark 2016). However, diversity may be a misleading indicator when evaluating threats to rare species, since a high number of species does not necessarily equal species of high conservation value.

Contrasting findings, regarding the relationship between vegetation and climbing activities, could reflect natural variation in plant communities (Nuzzo 1996) and cliff site topography but may also be caused by study design (Holzschuh 2016). Not controlling for biotic and abiotic differences between climbed and unclimbed sample cliff sites can result in potential selection bias (Holzschuh 2016) and lead to muddied or contradictory results. Unfortunately, research that controls for additional factors instead of just climbing activity itself is scarce, but considering and minimizing differences between climbed and unclimbed sample cliff sites is necessary to learn about the actual impact of climbing activity.

In this study, a climbing treatment was applied to a previously unclimbed sandstone boulder. It was monitored how the impact on lichen cover developed with the number of climbing ascents on the boulder. The data allows contrasting two management options for climbing activities in semi-natural settings: (1) If climbing activity causes only little damage until a threshold, managing activities within this limit would allow for sustainable climbing. (2) In contrast, if damage by climbing activity is highest at the beginning, with most of the lichen cover lost within few ascents, management should focus climbing activity on few selected sites and prevent any activity on other sites, thus keeping them undisturbed.

Methods

This study quantifies the resistance of previously undisturbed lichen communities to climbing activity by adapting the established experimental setting used to quantify trampling on ground vegetation. For that purpose, a standardized experimental protocol is commonly used in order to quantify the resistance of a specific plant species or community (Cole & Neil 1993). The relative vegetation cover is documented before, in between and after the treatments and is continuously plotted against the respective number of ascents. The trend of the resulting curve can be approximated with a regression curve, indicating a relative stabilization of cover reduction over time. This study uses a similar experimental approach, adopting the trampling resistance protocol to a vertical cliff face, while continuously monitoring lichen cover reduction.

This study focusses on sandstone rock, which is a popular rock type among climbers due to its high friction coefficient. Sandstone is very porous and shows high water absorption (Kılıç et al. 2008) and is therefore an ideal substrate for many local lichen species. Sandstone lichen appear to be especially vulnerable to climbing (Adams & Kamil 2012). An undisturbed sandstone boulder with characteristics attractive for climbing was selected for this study. Its vertical rock face is about 4 m tall, with numerous pockets and ledges serving as holds. The boulder is located 100 m away from the nearest path in the forest (49°55′03.3″ N, 11°30′26.8″ E, see Figure 1). We found no signs of previous climbing activity, such as chalk marks or ground vegetation trampling, therefore, we consider this specific boulder unclimbed. After the landowner and local authorities granted permission, the study was conducted from 24 June to 7 July 2020. During the study period, the weather was dry with no precipitation. Temperature and relative humidity ranged from 19–26 °C and 45–75%, respectively. The boulder was covered with lichen and bryophytes, which were not identified to species level. On the route chosen, only lichen occurred, with no bryophytes near the holds.

Figure 1. Location and picture of sandstone boulder used in study. All holds are visible (© openstreetmap.org contributors).

During the study period of eight days, a daily treatment of 50–100 climbing ascents was applied at seven days, resulting in a total of 500 ascents. The same holds for hands and feet were used for all ascents. The treatment was applied by two people weighing 64 kg and 68 kg and wearing regular climbing shoes. Both topped out after each ascent and returned to the bottom on a different way. No chalk or brushes were used to increase friction. At 14 points in time (before the treatment, after 10, 20, 30, 50, 100, 150, 200, 250, 300, 350, 400, 450 and 500 ascents), photographs were taken from 4 holds, of which 2 were footholds (FH1, FH2), 1 was a handhold (HH) and 1 was a combined hold for hands and feet (CHF) (Figure 2). The digital camera used was a Sony Cybershot DSC-T99.

To ensure the photos were taken from the same angle and section, a square 20 × 20 cm frame was used, but alas, this could not be achieved in every case. Due to small variations of exposition, angle and resolution, the images are not perfectly identical and possibly caused variation in cover estimation. Using more sophisticated equipment, such as stationary cameras and exposure units, sufficiently similar pictures can be taken to use automated computerized analysis methods. The assessment of the 3D hold topography was not possible due to equipment limitations. The extent of the holds in depth direction could not be accurately measured, so the lichen cover might be underestimated due to perspective distortion.

The presented results only apply for lichen dwelling on Middle European sandstone. Future studies on different rock types and climate zones are needed for assessing possible differences in the impact of climbing activities under respective regional conditions.

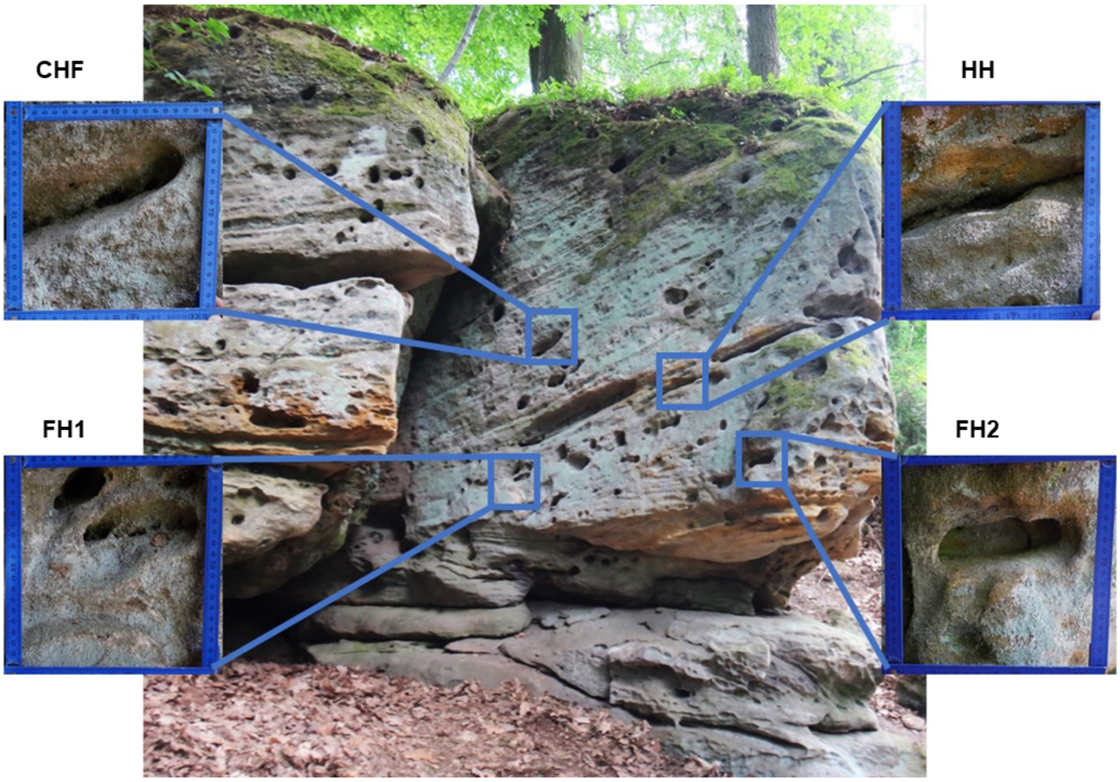

Figure 2. Positions of Footholds 1 and 2 (FH1, FH2), Handhold (HH) and Combined Hand- and Foothold (CHF) on the boulder used in study.

For lichen cover estimation, the photographs were cropped to remove the frame. They were also edited to optimize exposition, contrast and colour saturation for lichen identification. Cover was estimated visually using a 10 × 10 layover grid with each cell being 2 × 2 cm, as suggested by Reeding [26]. The relative lichen cover was recorded separately for each grid cell in each of the 52 photos. The mean of all cells represented the relative lichen cover for the respective number of ascents at that hold. The order of the photos was randomized to prevent bias during cover estimation. The relationship between estimated lichen cover and the number of ascents was analysed using segmented regression with unknown breakpoints (Muggeo 2017). Model performance was compared with standard linear regression. Analyses and visualizations were implemented in R version 4.0.3 (R Core Team 2021).

Results

Climbing activity reduced lichen cover (Table 1). The effect is very localized and concentrates on the immediate surrounding area of the holds. The loss in lichen cover is accompanied by significant rock abrasion (Figure 3).

Table 1. Development of lichen cover in the 20 × 20 cm squares around the holds before and after climbing treatment at Footholds 1 and 2 (FH1, FH2), Handhold (HH) and Hand- and Foothold (CHF).

	Lichen Cover Unclimbed		**Lichen Cover Climbed**		**Change in Lichen Cover**	
	Relative	**Total [cm²]**	**Relative**	**Total [cm²]**	**Relative**	**Total [cm²]**
FH1	84.9%	339.5	70.1%	280.3	−14.8%	−59.2
FH2	94.8%	379.1	82.1%	328.3	−12.7%	−50.8
HH	74.3%	297.3	75.4%	301.4	1.0%	4.1
CHF	94.6%	378.4	85.3%	341.1	−9.3%	−37.3

Before the climbing treatment, the relative lichen cover was high (74.3–94.8%). The complete treatment of 500 ascents reduced the lichen cover by 4.2–9.5% to 70.1–85.3% overall. The lichen cover around the Handhold (HH) did not change, while the cover around the Footholds (FH1 and FH2) decreased by 12.7% and 14.8%, respectively, resulting in a total loss of 50.8 cm² and 59.2 cm². The Combined Hand- and Foothold (CHF) showed a reduction of 9.3% or 37.3 cm² in the lichen cover.

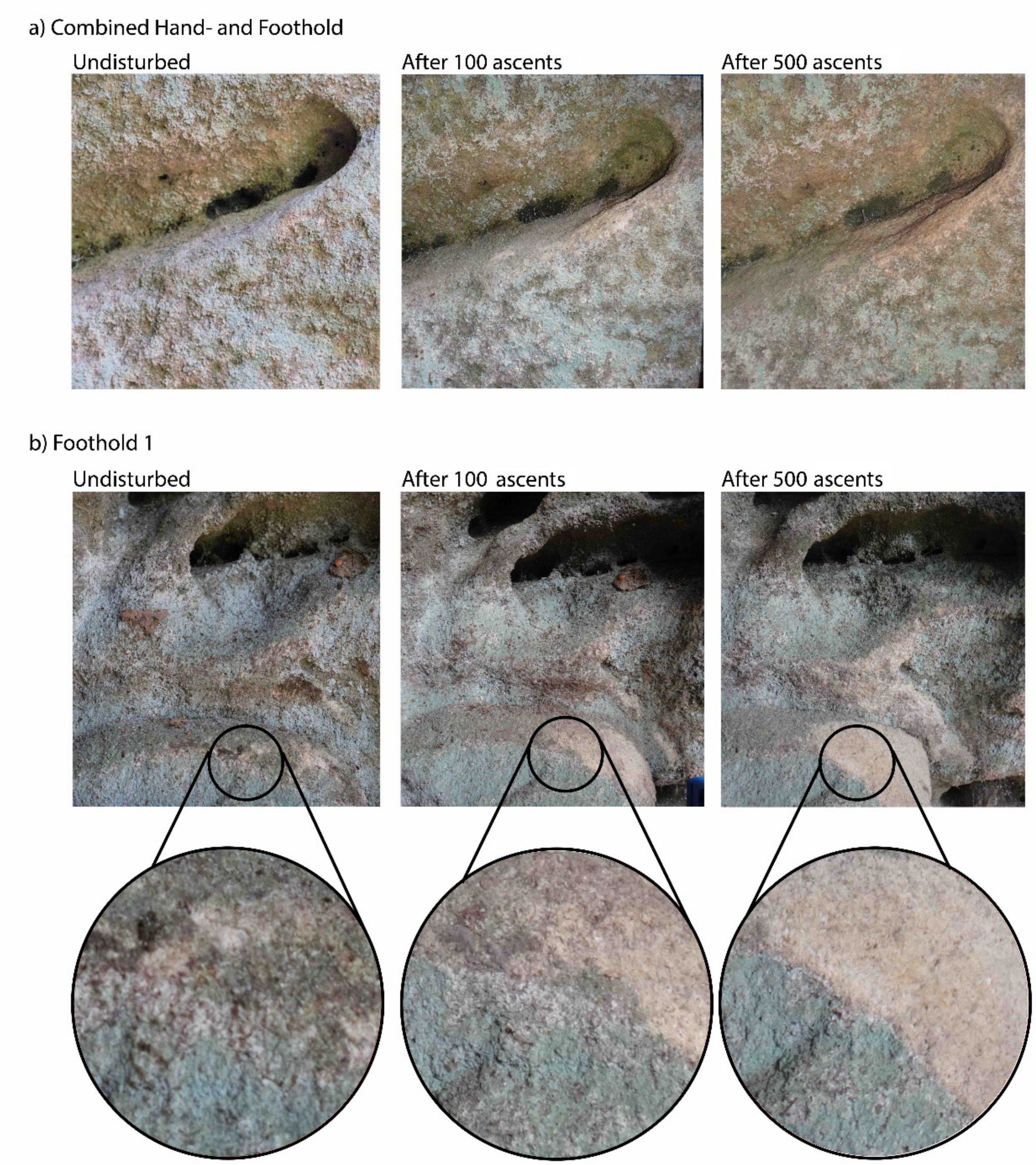

Figure 3. Images of (**a**) Combined Hand- and Foothold (CHF) and (**b**) Foothold 1 (FH1) after 0, 100 and 500 ascents. For FH1, exemplary details show abrasion over the course of the study.

Breakpoint estimates for Foothold 1 (FH1), Foothold 2 (FH2) and the Combined Hand- and Foothold (CHF) indicate a much faster decline in lichen cover within the first 50–100 ascents (Table 2, Figure 4). The decrease in lichen cover per ascent lessens by about a factor of 10 after the breakpoint. The models analysing the relationship between lichen cover and the number of climbing ascents are non-significant for the Handhold (HH), suggesting a much lower effect of climbing at the Handhold.

Table 2. Model characteristics of the segmented linear regression and comparison to linear regression as well as a null model with zero slope. Breakpoint and slope estimates are provided with standard error (±).

	FH1	**FH2**	**HH**	**CHF**
Breakpoint estimate	50.0 ± 11.7	58.1 ± 11.6	-	100.0 ± 38.5
Slope before breakpoint	−0.195 ± 0.055	−0.116 ± 0.024	-	−0.061 ± 0.027
Slope after breakpoint	−0.012 ± 0.003	−0.014 ± 0.002	-	−0.003 ± 0.003
AIC null model	87.4	83.9	54.2	72.9
AIC linear model	71.8	59.8	56.1	60.0
AIC segmented model	50.6	43.3	54.5	45.9
p-value segmented model	0.005	<0.001	Non-significant	0.046
R^2 linear model	0.72	0.85	-	0.66
R^2 segmented model	0.95	0.96	-	0.91

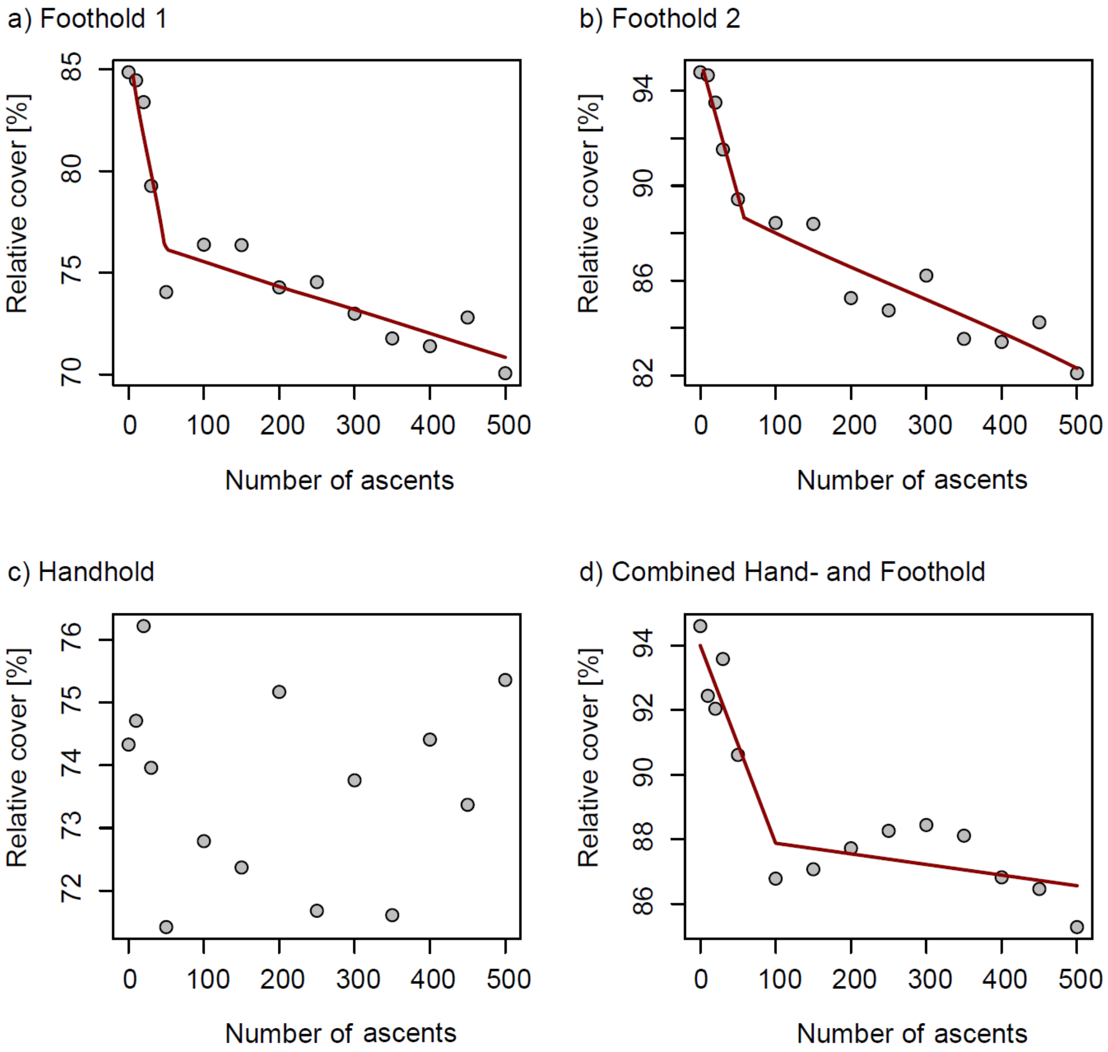

Figure 4. Relative lichen cover and number of ascents at Foothold 1 (**a**), Foothold 2 (**b**) and Combined Hand- and Foothold (**d**) with segmented breakpoint regression. The Handhold (**c**) showed no significant relationship between relative lichen cover and the number of ascents.

Discussion

This is the first study to assess the alteration in lichen cover on a previously unclimbed sandstone boulder during a climbing treatment. Since we observed the same boulder before, during and after climbing treatment, we circumvented potential observation bias that can occur when comparing different sites (Holzschuh 2016, Bogess et al. 2021). Although based on the observations of a single boulder with only four holds, the results allow a clear conclusion: The reduction in lichen cover is dependent on the number of climbing ascents. This effect is strongest in the very beginning of the climbing treatment (first 100 climbing ascents) and lessens over time without stopping entirely, even after 500 ascents. Hence, to protect lichen, management should focus on strictly separating and controlling climbed and unclimbed sites.

Lichen can grow on bare rock surface, where they generally are the most abundant and species-rich group (Holzschuh 2016). They are key organisms in shaping the species community at cliff sites and therefore a fit model to monitor shifts in cliff ecosystems (Baur et al. 2007). In accordance with the findings on ground vegetation trampling (Hill & Catherine 2009), the lichen cover reduction on rock shows continuous decline. The initial impact during the first 50–100 ascents is very high. Considering that the impact is very localized to the immediate surrounding area of the holds, it is possible to explain the impact mechanism on lichen: During the first 50–100 ascents, the lichen at the immediate surrounding area of the holds are removed. On the following ascents, further cover is only removed when a foot deviates from the ideal hold position (Figures 3 and 4). As a result, the cover reduction stabilizes over time. When climbing, the tip of the climbing shoe sole is the preferably used support area of the shoe. The observed total cover loss of 50–59 cm² at the footholds is roughly 1.5 times the size of the climbing shoe tip (climbing shoe tip area of shoe used in study was 37 cm²). A more precise foot placement will therefore lead to a smaller reduction in lichen cover over time. The area loss at the combined hand and foothold (CHF) is smaller with only 37.3 cm², which can be explained by the smaller size of the support area at that hold, compared to the larger holds of Foothold 1 and 2 (FH1, FH2). The topography of the holds also contributes to the magnitude of lichen cover loss. This is in accordance with previous studies that found a smaller impact on cliff site vegetation at more difficult routes with smaller holds (Kuntz & Douglas 2006). In this study, only two people climbed the boulder, always using the exact same holds. Other climbers may use different holds, resulting in higher cover reduction. The use of brushes and chalk would probably enhance the rock abrasion as well. Preliminary work has found chalk to influence algae positively and moss and lichens negatively on cliffs (Pereira 2005, Hepenstrick et al. 2020).

Notably, the effect of 500 ascents was not observed at handholds but only at footholds or combined foot and handholds. Our results implicate different impact mechanisms of feet and hands in climbing activities. A possible explanation is the higher reaction force applied by feet when holding on to a vertical wall (Noé et al. 2001). In the quadrupedal position, when the body is supported by both hands and feet, a 33% higher force is applied to the footholds, compared to the handholds. Even higher forces occur when lifting one foot of the wall. Additionally, climbing shoe soles are less elastic (Young's modulus = approx. 7.33 MPa (Hale et al. 2021)) than the skin of fingers (Young's modulus = approx. 0.03 MPa (Yang et al. 2018)). This leads to a higher load on the top layer of the uneven rock surface, while skin is deforming and adapting to the micro topography of the surface, distributing the load to a larger area and more evenly. Moreover, the rubber could lead to more abrasion. In climbing, the slipping of feet seems to occur more frequently than the slipping of hands, which might be explained by more precise positioning of the latter.

With the onset of climbing activity, lichens are not only damaged directly by contact with finger skin or shoe sole but indirectly by the removal of sandstone substrate due to abrasion. Sandstone, as a rock type, has the lowest abrasion resistance (Kılıç et al. 2008) and lichen on that substrate are therefore the most vulnerable to being removed together with the top rock layer (Adams & Kamil 2012). Since, in this study, most rock abrasion and loss of lichen cover happened at footholds, we suspect that the loss of lichen cover was mostly caused indirectly by rock abrasion. In contrast, at handholds, less lichen cover was lost and less rock abraded. Since lichen, except for crustose lichen, are known to seal off the rock surface and prevent erosion (Steinbauer et al. 2013), rock may be doubly threatened to abrade when lichen cover decreases. Although this study found the loss of lichen cover to be small and very localized, rock abrasion is a serious matter which affects boulders and whole cliff sites. Future studies should focus on the ability to regrow previously removed lichen in order to determine whether the effect is temporal or permanent. Since climbing activities are mostly seasonal sports, climbed as well as unclimbed cliff sites can be studied to research lichen rehabilitation.

When searching for a suitable route, climbers tend to choose cliff sites covered with less lichen and vegetation to avoid slipping (Clark & Hessl 2015, Kuntz & Douglas 2006, Farris 1998). In addition, most times the rock surface is "cleaned" by removing all lichen, bryophytes and most vascular plants when a new climbing route is established. This is performed to make the new routes more attractive and safer by, e.g., reducing the risk of slipping. A "cleaned" surface helps to place hands and feet more precisely on the rock surface, creates a more direct contact between rock and hands/feet and allows a better 'grip', as climbers claim. This is yet another reason to declare specific cliff sites as climbed or unclimbed, contrary to regulating visitor numbers.

Cliff sites offer unique habitats, oftentimes populated by endemic species. The conservation and protection of cliff sites requires scientific knowledge about the impact induced by climbing activity in order to take evidence-based conservation measures. As climbing activities become more and more popular, the need for tangible conservation measures rises. This study contributes to the understanding of the impact mechanism of climbing on rock dwelling lichen on sandstone, with abrasion potentially being the most impactful physical damage for lichen at cliff sites.

Statements and Declarations

Competing Interest: The authors declare no conflict of interest.

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Data Availability Statement: Publicly available datasets were analysed in this study. This data can be found here: https://nolowimpactpossible.wordpress.com/ (accessed on 8 December 2021).

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References

Adams, M. D., & Zaniewski, K. (2012). Effects of recreational rock climbing and environmental variation on a sandstone cliff-face lichen community. *Botany*, *90*(4), 253–259. https://doi.org/10.1139/b11-109

Baur, B., Fröberg, L., & Müller, S. W. (2007). Effect of rock climbing on the calcicolous lichen community of limestone cliffs in the northern Swiss Jura Mountains. *Nova Hedwigia*, *85*(3), 429–444. https://doi.org/10.1127/0029-5035/2007/0085-0429

Boggess, L. M., Harrison, G. R., & Bishop, G. (2021). Impacts of rock climbing on cliff vegetation: A methods review and best practices. *Applied Vegetation Science*, *24*(2). https://doi.org/10.1111/avsc.12583

Boggess, L. M., Walker, G. L., & Madritch, M. D. (2017). Cliff Flora of the Big South Fork National River and Recreation Area. *Natural Areas Journal*, *37*(2), 200. https://doi.org/10.3375/043.037.0209

Chen, J., Blume, H.-P., & Beyer, L. (2000). Weathering of rocks induced by lichen colonization—A review. *CATENA*, *39*(2), 121–146. https://doi.org/10.1016/S0341-8162(99)00085-5

Clark, P., & Hessl, A. (2015). The effects of rock climbing on cliff-face vegetation. *Applied Vegetation Science*, *18*(4), 705–715. https://doi.org/10.1111/avsc.12172

Cole, D. N., & Bayfield, N. G. (1993). Recreational trampling of vegetation: Standard experimental procedures. *Biological Conservation*, *63*(3), 209–215. https://doi.org/10.1016/0006-3207(93)90714-C

deCastro-Arrazola, I., March-Salas, M., & Lorite, J. (2021). Assessment of the Potential Risk of Rock-Climbing for Cliff Plant Species and Natural Protected Areas of Spain. *Frontiers in Ecology and Evolution*, *9*, 611362. https://doi.org/10.3389/fevo.2021.611362

Deutscher Alpenverein e.V. (DAV). (n.d.-a). *Klettern in Deutschland – Zahlen, Daten & Fakten*. Retrieved August 21, 2020, from https://www.alpenverein.de/der-dav/presse/hintergrund-info/klettern-in-deutschland-zahlen-daten-fakten_aid_31813.html

Deutscher Alpenverein e.V. (DAV). (n.d.-b). *Sportklettern boomt!* DAV. https://www.alpenverein.de/wettkampf/klettern/wettkampf-abc/sportklettern-und-wettkaempfe-beim-dav_aid_10318.html

Farris, M. A. (1998). The effects of rock climbing on the vegetation of three Minnesota cliff systems. *Canadian Journal of Botany*, *76*(12), 1981–1990. https://doi.org/10.1139/b98-178

Hale, J., O'Connell, A., Lewis, R., Carré, M. J., & Rongong, J. A. (2021). An Evaluation of Shoe Tread Parameters using FEM. *Tribology International*, *153*, 106570. https://doi.org/10.1016/j.triboint.2020.106570

Harrison, G. R. (2020). *The Impact of Rock-Climbing Disturbance on Cliff Communities of the Linville Gorge Wilderness Area*. Appalachian State University.

Hepenstrick, D., Bergamini, A., & Holderegger, R. (2020). The distribution of climbing chalk on climbed boulders and its impact on rock-dwelling fern and moss species. *Ecology and Evolution*, *10*(20), 11362–11371. https://doi.org/10.1002/ece3.6773

Hill, R., & Pickering, C. (2009). Differences in resistance of three subtropical vegetation types to experimental trampling. *Journal of Environmental Management*, *90*(2), 1305–1312. https://doi.org/10.1016/j.jenvman.2008.07.015

Holzschuh, A. (2016). Does rock climbing threaten cliff biodiversity? - A critical review. *Biological Conservation*, *204*, 153–162. https://doi.org/10.1016/j.biocon.2016.10.010

Honegger, R. (1998). The Lichen Symbiosis—What is so Spectacular about it? *The Lichenologist*, *30*(3), 193–212. https://doi.org/10.1006/lich.1998.0140

Kelly, P. E., & Larson, D. W. (1997). Effects of Rock Climbing on Populations of Presettlement Eastern White Cedar (Thuja occidentalis) on Cliffs of the Niagara Escarpment, Canada. *Conservation Biology*, *11*(5), 1125–1132. JSTOR.

Kılıç, A., Atiş, C. D., Teymen, A., Karahan, O., Özcan, F., Bilim, C., & Özdemir, M. (2008). The influence of aggregate type on the strength and abrasion resistance of high strength concrete. *Cement and Concrete Composites*, *30*(4), 290–296. https://doi.org/10.1016/j.cemconcomp.2007.05.011

Kuntz, K. L., & Larson, D. W. (2006). Influences of Microhabitat Constraints and Rock-Climbing Disturbance on Cliff-Face Vegetation Communities. *Conservation Biology*, *20*(3), 821–832. https://doi.org/10.1111/j.1523-1739.2006.00367.x

Larson, D. W., Matthes, U., & Kelly, P. E. (2000). *Cliff ecology: Pattern and process in cliff ecosystems*. Cambridge University Press.

Lorite, J., Serrano, F., Lorenzo, A., Cañadas, E. M., Ballesteros, M., & Peñas, J. (2017). Rock climbing alters plant species composition, cover, and richness in Mediterranean limestone cliffs. *PLOS ONE*, *12*(8), e0182414. https://doi.org/10.1371/journal.pone.0182414

March-Salas, M., Moreno-Moya, M., Palomar, G., Tejero-Ibarra, P., Haeuser, E., & Pertierra, L. R. (2018). An innovative vegetation survey design in Mediterranean cliffs shows evidence of higher tolerance of specialized rock plants to rock climbing activity. *Applied Vegetation Science*, *21*(2), 289–297. https://doi.org/10.1111/avsc.12355

McMillan, M. A., & Larson, D. W. (2002). Effects of Rock Climbing on the Vegetation of the Niagara Escarpment in Southern Ontario, Canada. *Conservation Biology*, *16*(2), 389–398. https://doi.org/10.1046/j.1523-1739.2002.00377.x

Muggeo, V. M. R. (2017). Interval estimation for the breakpoint in segmented regression: A smoothed score-based approach. *Australian & New Zealand Journal of Statistics*, *59*(3), 311–322. https://doi.org/10.1111/anzs.12200

Noé, F., Quaine, F., & Martin, L. (2001). Influence of steep gradient supporting walls in rock climbing: Biomechanical analysis. *Gait & Posture*, *13*(2), 86–94. https://doi.org/10.1016/S0966-6362(00)00098-9

Nuzzo, V. A. (1996). Structure of cliff vegetation on exposed cliffs and the effect of rock climbing. *Canadian Journal of Botany*, *74*(4), 607–617. https://doi.org/10.1139/b96-077

Pereira, John. (2005). *The influence of rock climbing chalk on cliff plant communities*. WorldCat.org.

R Core Team. (2021). *R: A Language and Environment for Statistical Computing* [R]. R Foundation for Statistical Computing. https://www.R-project.org/

Reding, J. (2019). *Rock Climbing or Lichen Climbing? How Rock Climbing Impacts Bryophyte and Lichen Communities Within the Red River Gorge*. The Ohio State University. https://etd.ohiolink.edu/apexprod/rws_etd/send_file/send?accession=osu1562584961670604&disposition=inline

Schmera, D., Rusterholz, H.-P., Baur, A., & Baur, B. (2018). Intensity-dependent impact of sport climbing on vascular plants and land snails on limestone cliffs. *Biological Conservation*, *224*, 63–70. https://doi.org/10.1016/j.biocon.2018.05.012

Steinbauer, M. J., Gohlke, A., Mahler, C., Schmiedinger, A., & Beierkuhnlein, C. (2013). Quantification of wall surface heterogeneity and its influence on species diversity at medieval castles – implications for the environmentally friendly preservation of cultural heritage. *Journal of Cultural Heritage*, *14*(3), 219–228. https://doi.org/10.1016/j.culher.2012.06.003

Strumia, S., Buonanno, M., Aronne, G., Santo, A., & Santangelo, A. (2020). Monitoring of Plant Species and Communities on Coastal Cliffs: Is the Use of Unmanned Aerial Vehicles Suitable? *Diversity*, *12*(4), 149. https://doi.org/10.3390/d12040149

Tessler, M., & Clark, T. A. (2016). The impact of bouldering on rock-associated vegetation. *Biological Conservation*, *204*, 426–433. https://doi.org/10.1016/j.biocon.2016.10.004

The Outdoor Foundation. (2018). *Outdoor Participation Report*. The Outdoor Foundation.

Yang, Y., Wang, L., Yan, F., Xiang, X., Tang, Y., Zhang, L., Liu, J., & Qiu, L. (2018). Determination of Normal Skin Elasticity by Using Real-time Shear Wave Elastography: Normal Skin Elasticity on Real-time Shear Wave Elastography. *Journal of Ultrasound in Medicine*, *37*(11), 2507–2516. https://doi.org/10.1002/jum.14608

Manuscript 3 - The influence of recreational activities on temporal feeding patterns of the common kingfisher (*Alcedo atthis*)

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Abstract

Disentangling acceptable effects of recreational outdoor activities on wildlife from those with relevant long-term consequences for population development is a key aspect when managing recreational activities in areas with high ecological value, such as aquatic habitats. We investigated the effect of human activities on short-term feeding behaviour and long-term feeding frequency of the common kingfisher (*Alcedo atthis*) breeding at river sites. We monitored four breeding pairs, during the nestling rearing period at the river Regnitz (northern Bavaria, Germany) over a period of 25 days with 213 hours of observation. We monitored differences in feeding and perching activity between periods with varying level of human recreational activities. The study results suggest human activities have a minimal effect on the common kingfisher. The likelihood of the bird entering its nest decreases as the number of humans in the area increases ($p<0.001$). Specifically, when fast-approaching individuals (such as bikers) are present, the bird does not show up until they have passed. Despite the high levels of human activity (with an average of 76 people per hour at the most active site), the birds still displayed similar feeding frequencies (2-6 times per hour) as reported in the literature, with a peak in feeding activity in the middle of the rearing period. If all human activity were removed from the model, the frequency of feeding would increase by approximately 5%. At highly visited sites, the birds seemed to display signs of habituation. Over a longer period of time, only fishing and boating activities were identified as having an effect on the common kingfisher, but the effect was again small (4-5%). In conclusion, while the common kingfisher may react to human presence through avoidance and habituation, its reproductive success is likely not negatively affected by the observed levels of human activity at the studied sites.

Introduction

Outdoor recreational activities are often concentrated in areas with high ecological value (Türk et al. 2004). Such activities may affect and disturb wildlife (Venohr et al. 2018; Schafft et al. 2021) that is already under stress by agricultural practices and other anthropogenic influences (Ramankutty et al. 2018; United Nations et al. 2019; Ellis et al. 2021). Whether a disturbance caused by recreational outdoor activities increases existing pressure on species and negatively influences the development of local number of individuals is often unclear. Understanding human-wildlife interactions is important as outdoor recreational activities also facilitate ecological understanding und awareness, thus advocating nature conservation (Bell et al. 2007), while also being a lucrative economic sector and increasing the quality of life, as well as promoting physical and mental health (Stott 2019; BMU 2021; BMU 2023). Disentangling acceptable effects of recreational outdoor activities on wildlife from those with relevant long-term consequences for population development is a key aspect when managing these activities in areas with high ecological value. Recreational activity on or close to aquatic habitats is a prime example for the difficulty of such an assessment. Rivers and lakes often possess a high ecological value, but also provide opportunity for various water activities like canoeing, stand-up paddling (SUP), swimming, or shore activities such as fishing, running, cycling.

Paddling activities are extremely popular – kayaking is one of the fastest growing activities in the US and the German association Deutscher Kanuverband e.V. is the biggest canoeing association in the world. Although paddling activity is often not estimated to be a high-disturbance activity (Batten 1977; Tuite et al. 1984; Platteeuw & Henkens 1997), it causes serious problems for certain species (Bell et al. 2007; Stott 2019). Starting with the mechanical contact of the paddle and the turbulences it induces, water clearance and temperature can be altered. Together, these effects can lead to behavioural changes of fish, such as swarm coherence and activity phases. Spawn might be damaged and the risk of predation increases, while food availability decreases (Zauner & Ratschan 2004). Similarly, effects on dragonfly larvae can be critical, as sediment swirls get into the larva’s gills and impair the respiratory system. Turbidity may lead to developmental disorders and has a chance to drift larvae into untypical habitats (Schorr 2000). Additionally, boats may spread invasive species (Stasko et al. 2012). However, human presence itself, e.g. while performing recreational outdoor activities, can disturb wildlife, change animal behaviour and may affect the animal’s metabolic and circulatory system (Reichholf 2001, Tablado & Jenni 2017). During kayak-induced disturbance, swans show increased locomotion and less foraging activity, resulting in a 34% higher energy expenditure and affecting their general level of fitness (Clausen et al. 2020). Since the effect of recreational activities varies between species and location, it is difficult to capture the full extent of disturbances caused by specific outdoor activities (Batten 1977; Klein et al. 1995; Laursen et al. 2005; Alexandrino et al. 2016).

In order to assess the effect of human activities on wildlife, birds are suitable indicators as they are very mobile and thus able to select their habitat carefully (Suri et al. 2017). In general, the visibility of human activity to a bird is an important factor for its assessment, as well as speed, shape, noise, direction and distance (Tuite et al. 1984; Klein et al. 1995; Reichholf 1998; Glover et al. 2015; Clausen et al. 2020). Speed in particular is a very important factor in threat estimation. Accordingly, birds are more likely to perceive joggers as a disturbance relative to walkers (Glover et al. 2011; Lethlean et al. 2017). Fishing, sailing and rowing cause the strongest effects in terms of aquatic recreational activities. Canoeing activity impose a comparative low disturbance effect on birds, but unlike sailing boats, canoes are able to move to shallow areas that normally serve as refuge (Batten 1977; Mendez Roldan 2013; Glover et al. 2015). This is also the case for stand-up paddleboards (SUP's), which were found to be more disruptive than canoes due to the prominent human silhouette (Bull & Rödl 2018). Bird species assess potential disturbances differently because of varying traits like e.g. sensory abilities, vigilance effort, previous experience (Batten 1977; Tablado & Jenni 2017). In general, migrant species seem more sensitive towards disturbances while resident species are less affected (Burger & Gorchfeld 1991; Klein et al. 1995; Glover et al. 2011; MacGregor-Fors & Schondube 2011). Furthermore, the sensitivity to potential disturbances increases with bird size, as well as flock size (Batten 1977; Laursen et al. 2005; Thiel et al. 2008; Glover et al. 2011). Disturbed areas are poorer in terms of bird species and their territories (Bötsch et al. 2017). In terms of nesting, disturbances can lead to partial or complete nest abandonment, and to decreased nest attentiveness, thus increasing predation risk (Hockin et al. 1992; Baudains & Lloyd 2007; Bötsch et al. 2017; Zhang et al. 2017). However, not always does a reduced nest attentiveness lead to an increased mortality of offspring, as the adults seem to habituate to potential disturbances and return to their nests earlier (Hockin et al. 1992; Baudains & Lloyd 2007). This happens especially at sites with continuous and predictable activities that birds could perceive as disturbances (Platteeuw & Henkens 1997). Furthermore, disturbances influence feeding behaviour. Birds spend more time evading, thus reducing feeding time, which they sometimes shift to other daytimes (Tuite et al. 1984; Hockin et al. 1992; Mattes & Meyer 2001; Clausen et al. 2020; Fontúrbel et al. 2021). Disturbances sometimes force bird species to leave otherwise good habitats entirely (Hockin et al. 1992; Platteeuw & Henkens 1997). Therefore, regimentations aiming to protect wildlife within affected habitats are essential to minimise negative effects on wildlife. A sound knowledge about specific disturbance effects, and which human activities can be perceived as disturbing, enhances decision-making and regimentations (Schafft et al. 2021).

In this study, we investigate the effects of outdoor recreational activities on the feeding and perching behavior of the common kingfisher (*Alcedo atthis*) during its breeding season. In Germany, the IUCN Red List classifies the common kingfisher as vulnerable (EEA 2019) and in Bavaria as endangered (Bayerisches Landesamt für Umwelt 2022). Common kingfishers are small to middle sized (16-17 cm), diurnal birds that live close to rivers and small ponds. They mainly feed on fish, insects and amphibians (Bezzel 1985; Raven 1986; Wüst 1986; Heinzel et al. 1996; Čech & Čech 2015). They are plunge divers, meaning they hunt from a perching point or while hovering, then swiftly dive into the water, catch prey and quickly re-emerge again (Heinzel et al. 1996). Common kingfishers usually breed at the end of a burrow in a riverbank or other suitable bodies of water (Bezzel 1985). We expect common kingfishers to react immediately to human recreational activity by not entering their nest nor visiting their nest-adjacent perch, thus temporarily reducing feeding activity. We also expect the birds to compensate this reduction during periods with low disturbance levels and investigate if this compensation is adequate to maintain a sufficient feeding frequency. Additionally, we investigate whether common kingfishers are able to habituate to human recreational activities. We investigate if the birds show fewer or diminished responses to human activities over time or with varying activity frequency at different sites. For our analysis, we observe feeding patterns at individual nests and correlate changes in the pattern to presence and intensity of human activities using a glm approach.

Methods

In this study, we observed the feeding and perching behaviour of kingfishers in front of their nesting *burrows* and documented human activities. We investigated how these activities affected the overall daily feeding behaviour, following an approach proposed by Mattes and Meyer (2001) and Kipping (2018).

From 13 May until 7 June 2021, we directly observed four nests of common kingfishers. Over the day, activity frequency is higher in the morning hours, with common kingfishers flying and scanning. For our observations, we divided the day evenly into four observation slots, starting 30 min before sunrise and ending 30 min after sunset. According to Isotti and Consiglio (1997), this time frame ensures capturing the activity of kingfishers sufficiently. Observations took place for 2-3 slots per day, which were randomly assigned to any of the 4 nests while trying to prevent two observations on the same day at the same nest. Overall, we monitored activity at the nests on 25 days, during 52 slots, for a total of 12794 minutes (ca. 213 hours) of observations.

All four observed nests are situated at the river Regnitz or its tributaries in or around the city of Bamberg, Bavaria, Germany (Figure 1). The ecological condition of the river Regnitz is categorized as unsatisfactory, but some tributaries reach a moderate ecological condition. The River Regnitz is an attractive canoeing destination. Vilches found that kingfisher feed on the most abundant fish species (Vilches et al. 2019). In the Regnitz these are bleak (*Alburnus alburnus*), roach (*Rutilus rutilus*), brown trout (*Salmon trutta*), topmouth gudgeon (*Pseudorasbora parva*) and common dace (*Leuciscus leuciscus*) (Knott et al. 2019). For our observations, we took note of all human activity in the vicinity. Nesting site 1 (park) was located in a popular park in Bamberg, at a small tributary of the Regnitz (overview in Figure 1). The nest was close to the water surface and has been used by common kingfishers for at least 4 years (personal information). Traffic via water is rare at the location. The nest was about 7 meters away to one of the main paths, exposing it to pedestrians, bicycles and dogs. All other locations are situated 7-8 km south of the city of Bamberg. Nesting site 2 (river) was located close to a passenger ferry, next to a large meadow, frequently used for recreational activities such as sunbathing, swimming and fishing. On the other side of the river, a suitable entry point for water sports, a small car park and a few allotments were located. The nest is located at a tall escarpment. A local sign clearly prohibits accessing the area. Nesting site 3 (meadow) was also located at the Regnitz. The nest was in an escarpment of a seldom-managed meadow next to the Regnitz. Here, recreational and agricultural activities occur rarely, but it is often uses as a fishing spot. Nesting site 4 (stream) was located at a small stream that connects the Regnitz and the Main-Danube channel. The stream lies in a steep dip, next to a small field path, with dense vegetation on both sides. The nest is in a burrow in the escarpment of the stream.

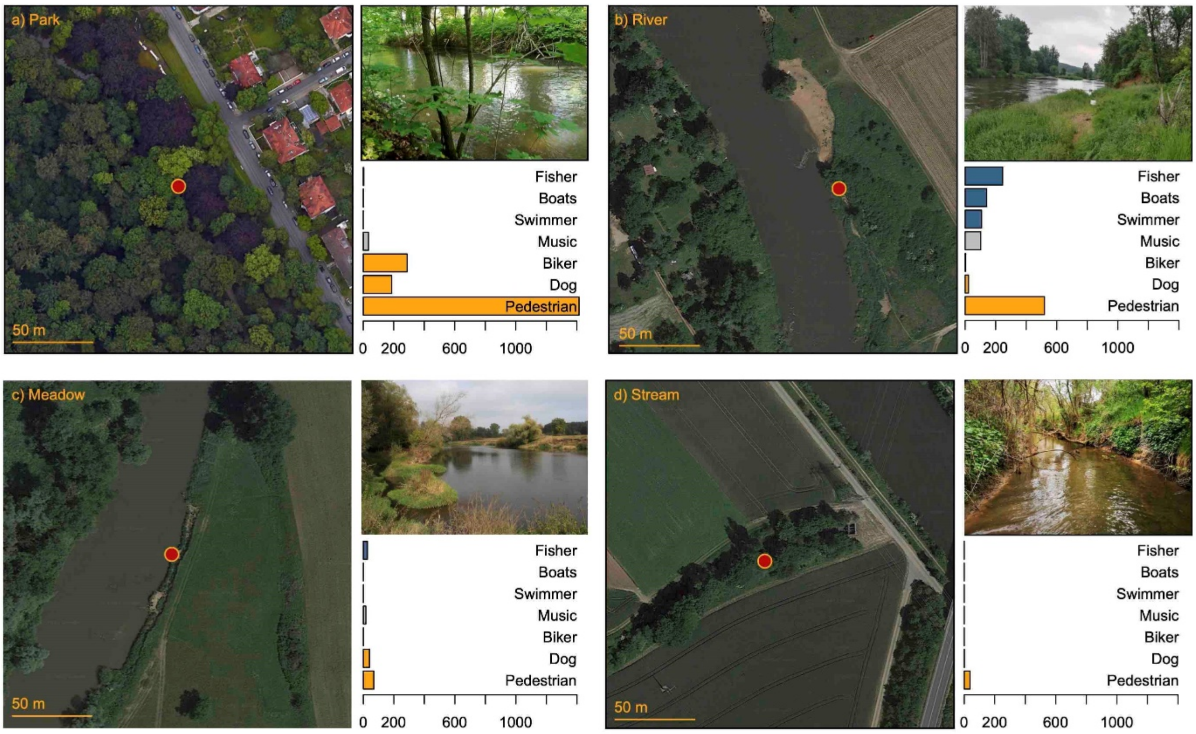

Figure 1: Overview on natural setting and human activities for the four nesting sites. Horizontal bar plots indicate the number of minutes with at least one of the indicated human activities. Areal views via Google Earth.

In order to minimise disturbance through the observers themselves, we used camouflaged nets and tents when feasible, and kept a distance as far as possible to the nest. However, the distance between nest and observer varied due to field conditions. At nesting site 4 (stream), we were only able to sit 20 m away from the nest, whereas the distance at nesting site 3 (meadow) measured up to 100 m. At nesting site 1 (park), in order to avoid attention, we were unable to build up suitable equipment. Instead, we choose a spot where the common kingfisher did not show any signs of increased vigilance. For the observations, we used binoculars (Nikon Japan 10 x 25 5.2°) and a spotting scope (TS Final 80 APO Spektiv & KOWA Prominar TSN-3). During the monitoring, we noted bird behaviour, namely the entries and exits in and out of the nesting burrow as an indication for a feeding event, duration of perching behaviour in front of the nesting burrow and instances of a common kingfisher flying away. We are aware, that there is not always a feeding event when a bird enters its nest during the rearing period. For the sake of our study, we allowed for this simplification and used instances of a bird entering as a proxy for the bird feeding its offspring.

During our observations, we assessed all human activities within 70 m from the nest. All observed activities were of recreational nature and could be grouped into categories like stand-up-paddling, canoeing, kayaking, fishing, photographing, walking, sunbathing, running, cycling, swimming, presence of dogs, cars and music audible to the observer. We estimated the distance of every human activity to the nesting burrow. Additionally, we noted weather status, and derived the average day temperature from the German Weather Service. We documented our findings on a minute-by-minute basis, with each human activity recorded for the duration of each minute it took place. At nesting site 1 (park), the occurrence of human activity events was at times very frequent, with several activities taking place within the same minute. In these periods, we counted all observed activities and divided them by the minutes that had passed.

When leaving their nest for good, fledglings often do so early in the morning (Bezzel 1985), which makes it difficult to observe this moment. Thus, we were only able to observe fledglings leaving their nest at nesting site 4 (stream). For all other locations, we had to estimate the fledgling date from the observed decline in feeding frequency over the observation period. We monitored all locations as long as we observed the parental common kingfisher entering or leaving the nest frequently. If, after three hours of monitoring at the end of the rearing period, we observed no feeding behavior, we determined that the fledglings had left their nest since the last monitoring session. We removed the time spent observing empty nests (overall 440 minutes) from the analyses. We had to remove another 184 minutes of observation as the declining visibility at dawn prevented a reliable observation, resulting in overall 12170 minutes of observation used in the analyses.

We analysed the data in two approaches: on a minute-based scale and on an hour-based scale. The minute-based scale provides insights into which parameter influences the probability of a bird entering its nest or perching during human activity close to the site, whereby the hour-based scale allows to discern if feeding or perching frequency changes with human activity levels. When aggregating the minute-based data (n=12170) to hours, observation hours with less than 50 minutes of observation were removed from the data. This resulted in overall 177 hours of observation used in the hour-based analyses.

We used generalised linear mixed effect models, with locations as random effects and a binomial error distribution, for examining the probability of a bird entering its nest or perching in dependence of human activity and other explanatory variables. We implemented the analysis of the minute-based data in three different approaches (models). Each model estimates the probability of a common kingfisher entering the nest or perching nearby in dependence of weather conditions (rain and temperature) as well as different ways of quantifying human activities. In a first model (model 1), human activity was quantified as the overall number of people present during an observational unit (minute). In a second modelling approach (model 2), only periods with human activity were analysed taking the distance of the activity as the explanatory variable. At last, we investigated single human activity classes (pedestrians (including promenaders and joggers), bikers, dogs, boats (including canoes, kayaks and SUPs), fisher, swimmer and music) for a possible effect on the probability of the common kingfisher entering or perching in front of its nest burrow. For each model, we removed non-relevant variables using stepwise model selection.

The hour-based data were analysed similarly. To assess changes in feeding behaviour, we used the number of times a bird was entering its nest, or perching nearby, per hour as the dependent variable. Aggregated entry or perching “events" (sum over one hour) constitute count data, which is why we used a Poisson error distribution in the hour-based model.

The analyses with multiple models and two different approaches (feeding and perching), were repeated for each single locations using generalised linear models with similar model setting as implemented for the mixed effect models (for more information see tables in appendix). For the statistical analysis, we used the programming language R (Version 4.1.0) within RStudio and the packages dplyr (Wickham et al. 2023), gdata (Warnes et al. 2022), ggeffects (Lüdecke et al. 2023a), lme4 (Bates et al. 2022), lubridate (Grolemund et al. 2023), performance (Lüdecke et al. 2023b), sjPlot (Ludecke et al. 2022), stargazer (Hlavac 2022), tidyverse (Wickham & RStudio 2023) and visreg (Breheny & Burchett 2020).

Results

General observations

For this study, we observed four breeding pairs of common kingfishers during the first breeding period in spring 2021 on 25 days. Across all sites, the common kingfishers’ activity near its nest (feeding and perching) was peaking around midway of the observed breeding period ($p<0.001$; Figure 2b and 3b) and increasing with daylily temperature ($p<0.001$; Figure 2c and 3c). Overall feeding activity was highest at nesting site 3 (meadow), with 5.5 ± 4.2 (mean ±standard deviation) entries per hour, and lowest at nesting site 1 (park) with 1.9 ± 2.1 entries per hour (Table 1). The longest time spend perching in front of the nesting burrow was found at nesting site 3 (meadow) with 10.7 ± 5.3 minutes per hour. Interestingly, at nesting site 1 (park) we found a similar time spend perching as compared with the other sites (6.7 ± 9.4 minutes per hour, Table 1).

Table 1: Overview of entry and perching behaviour at all four nesting sites

	Nesting site 1 (park)	Nesting site 2 (river)	Nesting site 3 (meadow)	Nesting site 4 (stream)
Total observation [minutes]	3616	2925	2216	3413
Number of entries per hour	1.9 ± 2.1	3.8 ± 2.8	5.5 ± 4.2	3.2 ± 2.7
Accumulated time spend perching per hour [min]	6.7 ± 9.4	7.8 ± 6.3	10.7 ± 5.3	7.0 ± 7.4

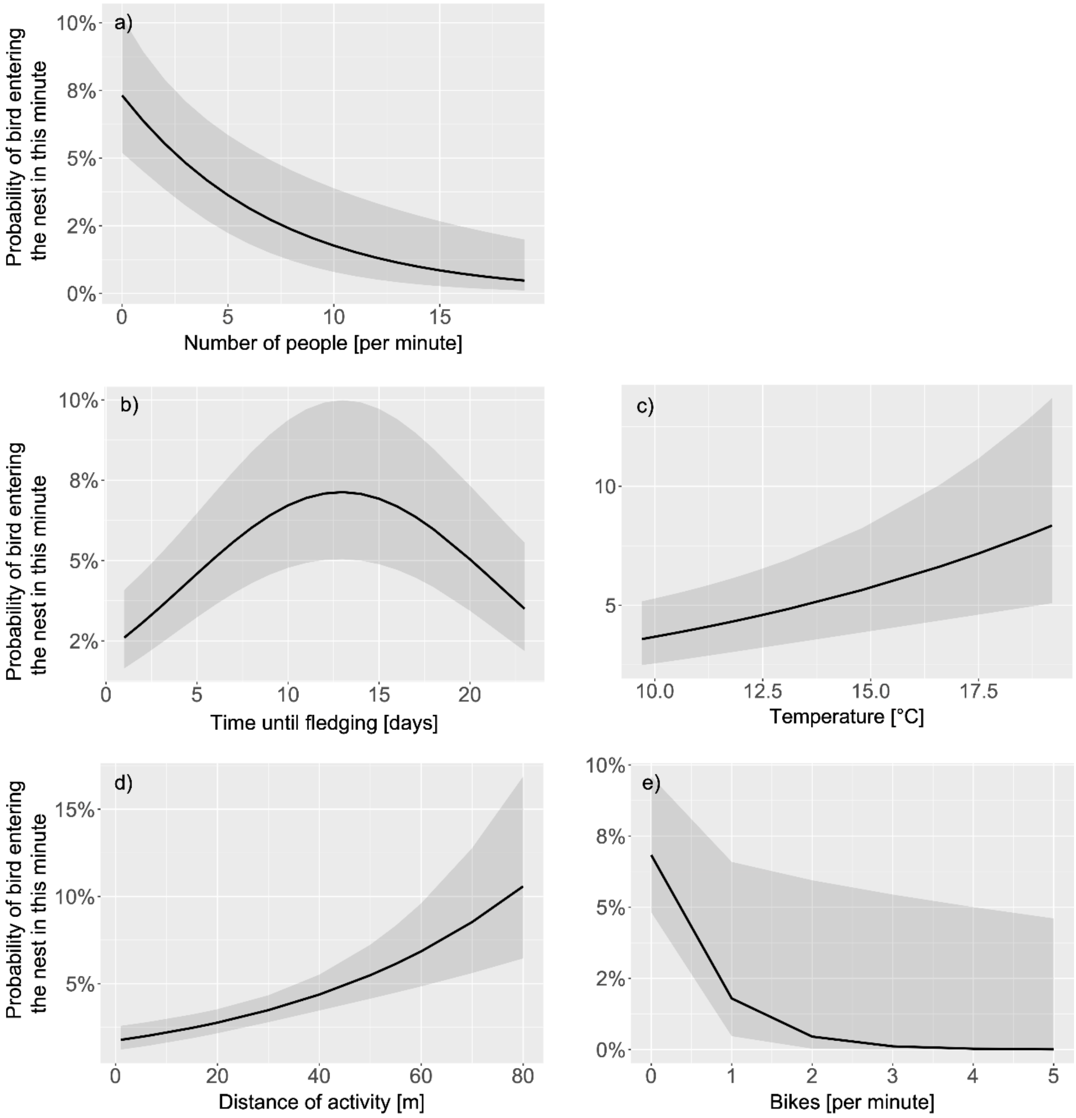

Figure 2: Change in the probability of a common kingfisher entering its nest (y-axis) with a) the number of people, b) the time until the young birds would be fledging and c) temperature (all from model 1, see table 2). The lower panel (d & e) depicts how the likelihood to observe a bird entering its nesting burrow declines with d) the distance to the activity (model 2) or with e) the number of bikers observed during that minute (model 3).

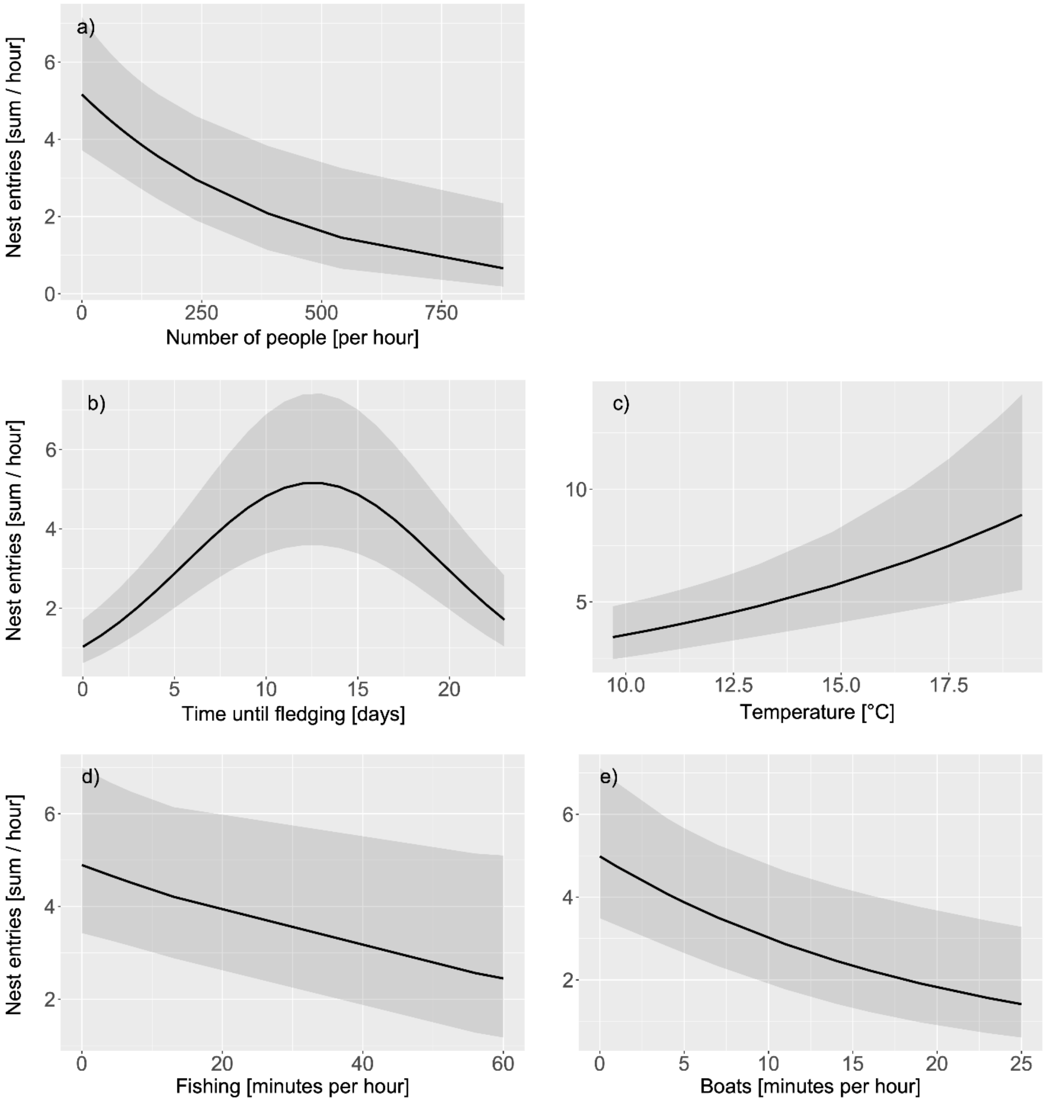

Figure 3: Feeding activity per hour declines with a) the number of people present close to the nest site (note scale of y axis), b) relates to the time to pass until the young birds fledge and c) increases with temperature (all model 1). Differentiating human activities reveals a decline in feeding with d) fishing and e) boating activity.

Human activity levels varied strongly between the four nesting sites. We observed the most activity events at nesting site 2 (river), where we recorded 3701 people over 2925 minutes of observation (on average 76 people per hour; note that a person is counted twice if present during two minutes of an hour). At this site, canoes, kayaks, stand-up-paddlers, fishers and swimmers were using the river. Additionally at the banks, people were sunbathing, promenading, cycling, barbecuing, walking their dog and played music. These human activities were intensive, but concentrated to busy periods. The number of observed human activities at nesting site 1 (park) was lower with 2776 over 3616 minutes (46 people per hour), but very constant on every given day. Pedestrians, cyclists, joggers and people walking their dog frequently used the path next to the small distributary (ca. 7 meters distance in front of the nest). Additionally, some groups of people played music and photographers were trying to capture pictures of the common kingfisher. Kayaks and canoes passed by only a few times. We observed very few human activities at nesting site 3 (meadow), where we observed mainly fishers with on average 5.7 people per hour, and nesting site 4 (stream) with 1.2 people per hour.

Effects of human recreational activities on feeding and perching behaviour

Personal observations during data collection indicate that the common kingfisher avoids human activity in front of its nesting burrow by waiting until the activity is over before approaching or entering its nest. At frequently visited sites, e.g. nesting site 1 (park) birds seem to be less susceptible to human presence. These observations are also found in the statistical analyses: Results of the analyses show that the probability of a common kingfisher entering its nest declines slightly when human activities occur (Table 2, figure 2). For instance, an increase in the number of people involved in recreational activities reduces the probability of the kingfishers entering its nest or perching nearby (Model 1, p-value< 0.001). Removing human activity entirely from the data by setting the number of people to 0 increase entering and perching probability by 6% (entering) or 4 % (perching), respectively. Furthermore, the further away an activity, the lower is the effect, and respectively the higher is the probability of the common kingfisher entering its nest (Model 2 entering, p-value<0.001). Personal observations during data collection indicate that bird individuals seem to observe human activity and wait, if possible, until humans have passed. Across all locations, biking (Model 3 entering, p-value<0.05) and music (p-value< 0.05) were the only single activities with a significant negative effect on the probability of a kingfisher entering its nest. However, removing bikers and music from the data increases the probability for observing the bird entering its nest only by 2.5%. When analysing the probability of a bird perching near its nest (Model 3 perching), aquatic activities like boating (p-value<0.05), fishing (p-value<0.05) and swimming (p-value<0.05) have a significant negative effect, in addition to music (p-value<0.05, coefficient: -0.99). Again, removing the significant human activities changes entering probability only marginally (by 2.8 %). Please also note that “significance” reflects a noise to signal ratio. Non-significant effects of single activity types could mean that those did not affect the common kingfisher, but they may also have occurred in too low numbers to test for effects.

Table 2: Results for three different models, using minute-based data across all four locations. The dependent variable is the number of entries by the common kingfisher into its nest or its visits. Non-significant variables are marked with “n. s.”. Variables excluded from a model are marked with “-“. *p<0.05; **p<0.01, ***p<0.001. “n” behind single activities indicates the number of minutes a respective activity was recorded. The last row (R^2) provides marginal R^2 values as calculated by R-package performance (Lüdecke et al. 2023b).

Dependent variable: Common kingfisher at nesting site (yes / no), using minute-based data						
	Bird entering its nesting burrow			Bird perching at nest site		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Constant	-3.70***	-4.03***	-3.68***	-2.50***	-1.71***	-2.48***
Rain	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.
Temperature	0.09***	n. s.	0.08***	0.07***	n. s.	0.07***
Daytime/minute	n. s.	n. s.	n. s.	-0.07**	n. s.	n. s.
Daytime/minute^2	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.
Day until fledging	0.25***	n. s.	0.23***	n. s.	-0.1 ***	n. s.
Day until fledging^2	-0.30***	n. s.	-0.27***	-0.36***	-0.24***	-0.36***
Distance of activity	-	0.02***	-	-	n. s.	-
Number of people	-0.15***	-	-	-0.10***	-	-
Pedestrian (n=2041)	-	-	n. s.	-	-	n. s.
Biker (n=293)	-	-	-1.39*	-	-	n. s.
Dog (n=250)	-	-	n. s.	-	-	n. s.
Boat (n=143)	-	-	n. s.	-	-	-0.35*
Fisher (n=277)	-	-	n. s.	-	-	-0.24*
Swimmer (n=108)	-	-	n. s.	-	-	-0.47*
Music (n=154)	-	-	-1.76*	-	-	-0.99*
Observations	12170	2456	12170	12170	12170	12170
R^2	0.03	0.06	0.06	0.05	0.04	0.06

Table 3: Results for two different models, using hour-based data across all four locations. The dependent variable is the number of entries by the common kingfisher into its nest or its visits. Non-significant variables are marked with “n. s.”. Variables excluded from a model are marked with “-“. *p<0.05; **p<0.01, ***p<0.001.

Dependent variable: Common kingfisher at nesting site (yes / no), using hour-based data				
	Bird entering its nesting burrow		Bird perching at nest site	
	Model 1	Model 3	Model 1	Model 3
Constant	-1.21*	-1.08*	1.19***	1.12***
Rain	n. s.	n. s.	n. s.	n. s.
Temperature	0.10***	0.09	0.04**	0.04*
Daytime/minute	n. s.	n. s.	n. s.	n. s.
Daytime/minute^2	n. s.	n. s.	n. s.	n. s.
Day until fledging	0.26***	0.26***	0.16***	0.17***
Day until fledging^2	-0.01***	-0.01***	-0.01***	-0.01***
Number of people	-0.003**	-	-0.001***	-
Pedestrian	-	n. s.	-	n. s.
Bikers	-	n. s.	-	n. s.
Dog	-	n. s.	-	n. s.
Boat	-	-0.05**	-	-0.06***
Fisher	-	-0.01*	-	-0.01**
Swimmer	-	n. s.	-	n. s.
Music	-	n. s.	-	n. s.
Observations	177	177	177	177
R^2	0.25	0.25	0.53	0.56

Discussion

In our study, we found a significant negative effect on common kingfishers' frequency of entering the nest or perching nearby by human activities, close proximity of these to the nest and the number of people involved in the activity. Disentangling the effects of the observed activities revealed strong differences between sites (see Appendix). We suggest to not focus on these differences in emergent activities as they may be driven by the number of observations (activities occurring in larger numbers are more likely to be selected as significant), activity restrictions at some locations and a possible habituation of the birds which also depends on its nesting site. However, the observed effects were minimal and did not inhibit the common kingfishers breeding success at the observed sites. At sites more hostile for the birds, it is reasonable to deduce that a similar small impact by human recreational activity could add up to a bigger negative effect on Common kingfisher. We deduce that the common kingfisher registers humans and their activities, but is able to habituate to them and rear its offspring without lowering its reproductive success. Our results are thus in accordance with Kipping (2018), who found that boating can interrupt common kingfishers behaviour but the general number of feedings is largely unaffected.

Comparing results of minute-based data with hour-based data, we found huge differences in which human activities significantly affected common kingfisher numbers of entering and perching events. Aggregating minute-based entering and perching events to an hour-based scale allowed to investigate whether the common kingfisher can compensate effects of human activity by approaching its nest when the activity disappeared again. For the minute-based data, fast approaching activities like biking significantly affect the birds, while for on the hourly scale, activities that take a long time affect common kingfisher the most. We suspect that activities indicated as significant by minute-based data are actually activities common kingfisher can evade. However, activities indicated as significant by hour-based data are unavoidable, since the bird would have to wait for too long.

Effects of human activities & habituation

Our data show that the number of people involved in human activities affects common kingfisher. To some extent, this factor indicates the general intensity of the human activity, with the more people present, the lower the number of entering events. Klein et al. (1995) observed in their study that birds show differing distribution patterns according to the visitor level, and González-Oreja et al. (2012) showed that species diversity decreased with increasing background noise levels. This also explains the sensitivity we observed towards music, which results in a decreasing chance of common kingfishers entering their nest.

Human activity that occurs repeatedly at the same distance and intensity might promote habituation, as these activities become more predictable and less threatening for the birds. Speed is one factor that determines the predictability of an activity (Platteeuw & Henkens 1997; Glover et al. 2011). Across all nesting site, biking, an activities that passes by the nest quickly, only significantly lowers common kingfishers activity when looking at the minute-based data. Another factor influencing predictability is the distance of the activity to the nest (Glover et al. 2011 & 2015; Kruger 2016). We found activities that stay in the nests proximity for a long time, e.g. fishing, significantly lower the birds activity on an hourly basis.

Number of young

As fledglings leave their nest site suddenly, we were only able to observe one occurence at nesting site 4 (stream). Based on observed feeding events, regular entries into the nesting chamber and observed behaviour of the adults luring the fledglings we assume a successful brood at all nest sites.

Kipping (2018) observed 2.75 feedings per hour, Vilches et al. (2013) 3.91 times per hour and Mattes and Meyer (2001) 2 - 3 times per hour. In our study, we were not able to distinguish between common kingfishers entering with or without food items, which is why we measured common kingfisher entering its nest instead of feeding their offspring. At nesting site 1 (park), the number of common kingfisher entering on an hourly scale did not decline, however it was relatively low in comparison to other locations. It is possible that the observed pair cared for a small number of nestlings, thus having a lower feeding frequency (Čech and Čech 2017). We conclude that for nesting site 1 (park), where we observed few feeding events but numerous perching events, the explanation of Mattes and Meyer (2001) seems more reasonable. They state that when finding low feeding activity and small responses to direct disturbances, it is the hunting activity that is mainly affected, instead of the feeding activity. Similarly, Burger and Gochfeld (1998) observed a reduction in foraging activity due to disturbances in shore birds, with individuals spending more time being vigilant and changing their location rather than foraging.

At nesting site 2 (river), the entering frequency with an average of 5.68 entries per hour is relatively high. However, this number hardly gives an explanation whether it results from high feeding frequencies during days with low human activity rates or if the breeding pair had to care for a big number of fledglings and therefore had to feed more items (Čech and Čech 2017).

Daily & seasonal activity

The peak of common kingfisher's daily activity differed between locations. Across all sites, the number of times a common kingfisher enters its nest increased during the first days after hatching, peaks and then decreased until the day of fledging. In the beginning, feeding activity mainly rises due to increasing energetic requirements of the growing nestlings and parental warming of them (Isotti & Consiglio 1997; Čech and Čech 2017). When parental warming stops, the feeding activity reaches its peak and soon starts to decrease again. This decrease slowly continues until the parents lure the juvenile out of the nest (Bezzel 1985; Mattes and Meyer 2001).

Interestingly, at nesting site 1 (park) the kingfishers' entering frequency showed no pattern, remaining relatively constant across the rearing period. Additionally, the rearing period at nesting site 1 (park) was the longest, with observations spanning 22 days. According to Čech and Čech (2017), if nestlings lack sufficient energy intake, competition between nestlings increases and thus their energy requirements, which results in an elongated rearing period. Therefore, we presume the lack of an entering event pattern at nesting site 1 (park) is due to the generally low number of entering events observed at this site, causing competition between nestlings and forcing parental kingfishers to compensate their low feeding frequency at a time when normally the rate should have already been decreasing.

At nesting site 2 (river), the number of entering events decreased across the season. The apparent lack of an increase at the start may be due to the delayed onset of the observations. However, this is not certain, as the first day of the feeding activity is unknown.

Limitations and further research

Due to relatively low temperature during the study period, most nesting sites were exposed to below average recreational activities, with various activities barely accumulating representative numbers. Only at nesting site 1 (park), visitation levels were high and constant across the study period. Additionally, the previous winter had been harsh, which might have affected the physical condition of parental kingfishers, and thus, clutch sizes and number of nestlings (Cepková et al. 2021). Furthermore, the assumption that the number of entries of a parental common kingfisher into its nest is representative for the number of feeding events (Mattes and Meyer 2001, Kipping 2018) might not be correct in all cases. In addition, despite taking all possible precautions, it is still possible that our observations affected the common kingfishers' behaviour. This especially applies to nesting site 1 (park), where we could not use any camouflage equipment. However, we did not observe any direct reactions of the kingfishers to the observations.

At nesting site 3 (meadow), the breeding pair started a second brood right next to their ongoing first brood. This made it difficult to distinguish between the two nests and might explain why the number of entering and perching events increased towards the end of the rearing period. At nesting site 1 (park) and 4 (stream), the birds used several branches for perching, making it easy to miss the separate perching events.

For this study, three different people were conducting the observations, which may have affected the data due to varying error propagation.

Management options

In 2012, Germany hosted between 9000 and 14 500 pairs of common kingfisher, thereof 1600 - 2200 in Bavaria. This number has been stable and even increasing until 2018 (European Environmental Agency 2016 & 2018; Bayerisches Landesamt für Umwelt 2022). Although common kingfisher are not threatened in Germany (Ryslavy et al 2020), in Bavaria it holds the status of being endangered (Bayerisches Landesamt für Umwelt 2022). The most commonly used conservation methods aimed at common kingfishers are ecological enhancement of the habitats, such as the restoration of the water quality, agricultural-related measures or simply the establishment of protected areas (European Environmental Agency 2016). These measures are especially valuable in terms of food abundance and supporting common kingfishers' capability to deal with certain environmental stressors. Moreover, so-called 'soft-measures' promote the improvement of information systems about the route, including entry points for boats and bivouac places, water levels, the ecology of the area and rules of conduct. These measures were already able to enforce nature conversation at the Müritz in Germany (Biedenkapp & Stuhrmann 2004). In order to lessen the effect of existing human recreational activity, nesting cover, like a small island, in front of the nest can shield kingfishers from views and create a small refuge (Hockin et al. 1992). Furthermore, additional measures aim towards temporal or long-term closures of specific areas to create resting zones (Roth et al. 2005), e.g. at the river Wiesent in Bavaria, Germany, canoeing is only allowed between May 5th and October 31th. Since we found in our study that human activity do not inhibit common kingfishers breeding success, closures and bans of activities might prevent habituation to human activities of this bird species. Without a baseline of activities to get used to, common kingfisher might feel extremely disturbed when a single activity occurs. Kingfishers are most likely to abandon their nests during their construction phase, meaning closures would be most efficient during that time (Davies 1982, Hockin et al. 1992, Bridge & Kelly 2003). Apart from that, other species might profit from said closures.

Supporting a flagship species such as the common kingfisher may increase recreationists understanding for regimentations and willingness to adhere to regional rules. Prohibiting access to specific areas, speciality without an apparent reason, is not a realistic solution. Recreational activities further wellbeing and mitigate physical and psychological problems. Finding solutions that benefit recreationists as well as wildlife is crucial. The common kingfishers at nesting site 1 (park) showed that breeding under great recreational pressure is possible. However, we expect that dealing with such a high human activity level will decrease their resilience to other environmental effects, such as predation, flooding or feed shortages.

Conclusion

We found human leisure activity to have only a minimal effect on feeding activity of the common kingfisher. The birds temporarily avoided fast human activities, e.g. biking, before entering their nest, but despite very high levels of human activity, common kingfisher displayed feeding frequencies, comparable to those observed without human activities. When we modelled our data to exclude any human activity, feeding frequency increased only slightly. While common kingfisher may thus react to human presence by avoidance and habituation, reproductive success is likely not negatively impacted in the study area.

Statements and Declarations

Competing Interest: The authors declare no conflict of interest.

Funding: This publication received no funding.

Data Availability Statement: The data and scripts used are available at https://github.com/AMSchweizer/ManualKingfisher

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Appendix

Effects of human recreational activity on feeding behaviour at specific nesting sites

Appendix Table 1: Nesting site 1 (park). For R^2 Tjur's R^2 was used.

Results for three different models, using minute-based data across all four locations. The dependent variable is the number of entries by the common kingfisher into its nest or its visits. Non-significant variables are marked with "n. s.". Variables excluded from a model are marked with "-". Coefficients are given for significant variables. *p<0.05; **p<0.01, ***p<0.001.

Dependent variable: Common kingfisher at nesting site 1 (yes / no), using minute-based data						
	Bird entering its nesting burrow			Bird perching at nest site		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Constant	-3.54***	-3.54***	-3.54***	-1.83***	-1.83***	-1.83***
Rain	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.
Temperature	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.
Daytime/minute	-0.46***	-0.46***	-0.46***	-0.21***	-0.21***	-0.21***
Daytime/minute^2	n. s.	n. s.	n. s.	n. s.	n. s.	-0.25***
Day until fledging	n. s.	n. s.	n. s.	-0.25***	-0.25***	-0.30***
Day until fledging^2	n. s.	n. s.	n. s.	-0.30***	-0.30***	n. s.
Distance of activity	-	n. s.	-	-	n. s.	-
Number of people	n. s.	-	-	n. s.	-	-
Pedestrian	-	-	n. s.	-	-	n. s.
Biker	-	-	n. s.	-	-	n. s.
Dog	-	-	n. s.	-	-	n. s.
Boat	-	-	n. s.	-	-	n. s.
Fisher	-	-	n. s.	-	-	n. s.
Swimmer	-	-	N/A	-	-	N/A
Music	-	-	n. s.	-	-	n. s.
Observations	3616	3616	3616	3616	3616	3616
R^2	0.01	0.01	0.01	0.02	0.02	0.02

Appendix Table 2: Nesting site 2 (river). For R^2 Tjur's R^2 was used.

Results for three different models, using minute-based data across all four locations. The dependent variable is the number of entries by the common kingfisher into its nest or its visits. Non-significant variables are marked with "n. s.". Variables excluded from a model are marked with "-". Coefficients are given for significant variables. *p<0.05; **p<0.01, ***p<0.001.

Dependent variable: Common kingfisher at nesting site 2 (yes / no), using minute-based data						
	Bird entering its nesting burrow			Bird perching at nest site		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Constant	-5.77***	-2.72***	-5.91***	-6.21***	-3.37***	-6.23***
Rain	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.
Temperature	0.23***	n. s.	0.24***	0.35***	n. s.	0.36***
Daytime/minute	n. s.	n. s.	n. s.	0.18**	n. s.	0.18**
Daytime/minute^2	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.
Day until fledging	n. s.	n. s.	1.00***	0.97***	n. s.	1.04***
Day until fledging^2	1.00***	n. s.	n. s.	-0.60***	n. s.	-0.54***
Distance of activity	-	n. s.	-	-	0.02*	-
Number of people	-0.16***	-	-	-0.21***	-	-
Pedestrian	-	-	-0.17**	-	-	-0.21***
Biker	-	-	n. s.	-	-	n. s.
Dog	-	-	n. s.	-	-	n. s.
Boat	-	-	n. s.	-	-	n. s.
Fisher	-	-	n. s.	-	-	n. s.
Swimmer	-	-	n. s.	-	-	-0.55**
Music	-	-	n. s.	-	-	n. s.
Observations	2925	2925	2925	2925	793	2925
R^2	0.01	0.00	0.01	0.05	0.01	0.05

Appendix Table 3: Nesting site 3 (meadow). For R^2 Tjur’s R^{2}was used.

Results for three different models, using minute-based data across all four locations. The dependent variable is the number of entries by the common kingfisher into its nest or its visits. Non-significant variables are marked with “n. s.”. Variables excluded from a model are marked with “-“. Coefficients are given for significant variables. *p<0.05; **p<0.01, ***p<0.001.

Dependent variable: Common kingfisher at nesting site 3 (yes / no), using minute-based data						
	Bird entering its nesting burrow			Bird perching at nest site		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Constant	-2.01***	-3.86***	-1.92***	-1.23***	-4.40*	-1.23***
Rain	-1.42*	n. s.	-1.42*	n. s.	n. s.	n. s.
Temperature	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.
Daytime/minute	n. s.	n. s.	-0.49*	-0.37***	11.77*	-0.37***
Daytime/minute^2	-0.32***	n. s.	-0.20*	-0.17*	-11.93*	-0.41*
Day until fledging	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.
Day until fledging^2	n. s.	n. s.	-0.49*	-0.41**	n. s.	-0.41**
Distance of activity	-	n. s.	-	-	0.04*	-
Number of people	n. s.	-	-	n. s.	-	-
Pedestrian	-	-	n. s.	-	-	n. s.
Biker	-	-	n. s.	-	-	n. s.
Dog	-	-	0.91*	-	-	n. s.
Boat	-	-	N/A	-	-	N/A
Fisher	-	-	n. s.	-	-	n. s.
Swimmer	-	-	N/A	-	-	N/A
Music	-	-	n. s.	-	-	n. s.
Observations	2216	89	2216	2216	89	2216
R^2	0.01	0.05	0.01	0.02	0.17	0.02

Appendix Table 4: Nesting site 4 (stream). For R^2 Tjur's R^{2}was used.

Results for three different models, using minute-based data across all four locations. The dependent variable is the number of entries by the common kingfisher into its nest or its visits. Non-significant variables are marked with "n. s.". Variables excluded from a model are marked with "-". Coefficients are given for significant variables. *p<0.05; **p<0.01, ***p<0.001.

Dependent variable: Common kingfisher at nesting site 4 (yes / no), using minute-based data						
	Bird entering its nesting burrow			Bird perching at nest site		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Constant	-2.67***	-2.92***	-2.67***	n. s.	-2.18***	n. s.
Rain	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.
Temperature	n. s.	n. s.	n. s.	-0.17***	n. s.	-0.17***
Daytime/minute	0.19*	0.19*	0.19*	n. s.	n. s.	n. s.
Daytime/minute^2	n. s.	n. s.	n. s.	n. s.	0.14*	n. s.
Day until fledging	0.28**	n. s.	0.28**	-0.44***	n. s.	-0.44***
Day until fledging^2	-0.28***	n. s.	-0.28***	n. s.	n. s.	n. s.
Distance of activity	-	n. s.	-	-	n. s.	-
Number of people	n. s.	-	-	n. s.	-	-
Pedestrian	-	-	n. s.	-	-	n. s.
Biker	-	-	N/A	-	-	N/A
Dog	-	-	n. s.	-	-	n. s.
Boat	-	-	N/A	-	-	N/A
Fisher	-	-	N/A	-	-	N/A
Swimmer	-	-	N/A	-	-	N/A
Music	-	-	N/A	-	-	N/A
Observations	3413	3413	3413	3413	3413	3413
R^2	0.01	0.00	0.01	0.02	0.00	0.02

Appendix Table 5: Nesting site 1 (park). For R^2 Tjur's $R^2$was used.

Results for three different models, using minute-based data across all four locations. The dependent variable is the number of entries by the common kingfisher into its nest or its visits. Non-significant variables are marked with "n. s.". Variables excluded from a model are marked with "-". Coefficients are given for significant variables. *p<0.05; **p<0.01, ***p<0.001.

Dependent variable: Common kingfisher at nesting site 1 (yes / no), using hour-based data				
	Bird entering its nesting burrow		Bird perching at nest site	
	Model 1	Model 3	Model 1	Model 3
Constant	n. s.	n. s.	n. s.	1.63***
Rain	n. s.	n. s.	n. s.	n. s.
Temperature	n. s.	n. s.	0.09*	n. s.
Daytime/minute	n. s.	n. s.	n. s.	n. s.
Daytime/minute^2	n. s.	n. s.	n. s.	n. s.
Day until fledging	0.18*	0.18*	0.31***	0.16***
Day until fledging^2	-0.01*	-0.01*	-0.05***	-0.01***
Number of people	n. s.	-	0.01***	-
Pedestrian	-	n. s.	-	0.01**
Biker	-	n. s.	-	n. s.
Dog	-	n. s.	-	-0.08**
Boat	-	n. s.	-	n. s.
Fisher	-	n. s.	-	-0.57*
Swimmer	-	N/A	-	N/A
Music	-	n. s.	-	n. s.
Observations	51	51	51	51
R^2	0.14	0.14	0.80	0.78

Appendix Table 6: Nesting site 2 (river). For R^2 Tjur's $R^2$was used.

Results for three different models, using minute-based data across all four locations. The dependent variable is the number of entries by the common kingfisher into its nest or its visits. Non-significant variables are marked with "n. s.". Variables excluded from a model are marked with "-". Coefficients are given for significant variables. *p<0.05; **p<0.01, ***p<0.001.

Dependent variable: Common kingfisher at nesting site 2 (yes / no), using hour-based data				
	Bird entering its nesting burrow		Bird perching at nest site	
	Model 1	Model 3	Model 1	Model 3
Constant	-3.12**	-4.08***	-3.33***	-3.68***
Rain	n. s.	n. s.	n. s.	n. s.
Temperature	0.22***	0.26***	0.27***	0.27***
Daytime/minute	n. s.	n. s.	n. s.	n. s.
Daytime/minute^2	n. s.	n. s.	n. s.	n. s.
Day until fledging	0.16***	0.20***	0.18***	0.31***
Day until fledging^2	n. s.	n. s.	n. s.	-0.01*
Number of people	-0.002**	-	-0.003***	-
Pedestrian	-	-0.02***	-	n. s.
Biker	-	n. s.	-	n. s.
Dog	-	n. s.	-	n. s.
Boat	-	n. s.	-	-0.05***
Fisher	-	n. s.	-	n. s.
Swimmer	-	n. s.	-	-0.03*
Music	-	n. s.	-	n. s.
Observations	42	42	42	42
R^2	0.57	0.58	0.85	0.87

Appendix Table 7: Nesting site 3 (meadow). For R^2 Tjur's R^{2}was used.

Results for three different models, using minute-based data across all four locations. The dependent variable is the number of entries by the common kingfisher into its nest or its visits. Non-significant variables are marked with "n. s.". Variables excluded from a model are marked with "-". Coefficients are given for significant variables. *p<0.05; **p<0.01, ***p<0.001.

Dependent variable: Common kingfisher at nesting site 3 (yes / no), using hour-based data				
	Bird entering its nesting burrow		Bird perching at nest site	
	Model 1	Model 3	Model 1	Model 3
Constant	n. s.	n. s.	1.83***	1.75***
Rain	n. s.	n. s.	n. s.	n. s.
Temperature	n. s.	n. s.	n. s.	n. s.
Daytime/minute	n. s.	n. s.	n. s.	n. s.
Daytime/minute^2	n. s.	n. s.	n. s.	n. s.
Day until fledging	0.43***	0.48***	0.16**	0.19***
Day until fledging^2	-0.02***	-0.24***	-0.01**	-0.01***
Number of people	n. s.	-	n. s.	-
Pedestrian	-	-0.29*	-	-0.39**
Biker	-	5.25*	-	6.52**
Dog	-	0.29*	-	0.38**
Boat	-	N/A	-	N/A
Fisher	-	n. s.	-	n. s.
Swimmer	-	N/A	-	N/A
Music	-	N/A	-	N/A
Observations	33	33	33	33
R^2	0.60	0.70	0.31	0.60

Appendix Table 8: Nesting site 4 (stream). For R^2 Tjur's R^2 was used.

Results for three different models, using minute-based data across all four locations. The dependent variable is the number of entries by the common kingfisher into its nest or its visits. Non-significant variables are marked with "n. s.". Variables excluded from a model are marked with "-". Coefficients are given for significant variables. *p<0.05; **p<0.01, ***p<0.001.

Dependent variable: Common kingfisher at nesting site 4 (yes / no), using hour-based data				
	Bird entering its nesting burrow		Bird perching at nest site	
	Model 1	Model 3	Model 1	Model 3
Constant	n. s.	n. s.	4.11***	4.11***
Rain	n. s.	n. s.	n. s.	n. s.
Temperature	n. s.	n. s.	n. s.	-0.14***
Daytime/minute	n. s.	n. s.	n. s.	n. s.
Daytime/minute^2	n. s.	n. s.	n. s.	n. s.
Day until fledging	0.25***	0.25***	-0.003***	n. s.
Day until fledging^2	-0.01***	-0.001***	-0.14***	-0.003***
Number of people	n. s.	-	n. s.	-
Pedestrian	-	n. s.	-	n. s.
Biker	-	N/A	-	N/A
Dog	-	N/A	-	N/A
Boat	-	N/A	-	N/A
Fisher	-	N/A	-	N/A
Swimmer	-	N/A	-	N/A
Music	-	N/A	-	N/A
Observations	51	51	51	51
R^2	0.44	0.44	0.71	0.71

References

Alexandrino, E. R., Buechley, E. R., Piratelli, A. J., Ferraz, K. M. P. M. de B., de Andrade Moral, R., Şekercioğlu, Ç. H., Silva, W. R., & Couto, H. T. Z. do. (2016). Bird sensitivity to disturbance as an indicator of forest patch conditions: An issue in environmental assessments. *Ecological Indicators*, *66*, 369–381. https://doi.org/10.1016/j.ecolind.2016.02.006

Bates, D., Maechler, M., Bolker, B., Walker, S., Bojesen Christensen, R. H., Singmann, H., Dai, B., Scheipl, F., Grothendieck, G., Green, P., Fox, J., Bauer, A., & Krivitsky, P. N. (2022). *lme4: Linear Mixed-Effects Models using "Eigen" and S4* (1.1-31) [R]. github.com/lme4/lme4/

Batten, L. A. (1977). Sailing on reservoirs and its effects on water birds. *Biological Conservation*, *11*(1), 49–58. https://doi.org/10.1016/0006-3207(77)90027-1

Baudains, T. P., & Lloyd, P. (2007). Habituation and habitat changes can moderate the impacts of human disturbance on shorebird breeding performance. *Animal Conservation*, *10*(3), 400–407. https://doi.org/10.1111/j.1469-1795.2007.00126.x

Bayerisches Landesamt für Umwelt. (2022). *Eisvogel (Alcedo atthis)*. https://www.lfu.bayern.de/natur/sap/arteninformationen/steckbrief/zeige?stbname=Alcedo+atthis

Bell, S., Tyrväinen, L., Sievänen, T., Pröbstl, U., & Simpson, M. (2007). Outdoor Recreation and Nature Tourism: A European Perspective. *Living Reviews in Landscape Research*, *1*. https://doi.org/10.12942/lrlr-2007-2

Bezzel, E. (1985). *Kompendium der Vögel Mitteleuropas—Nonpasserieformes* (1st ed.). Aula Verlag.

Biedenkapp, A., & Stührmann, E. (2004). *Tourismus, Naturschutz Und Wassersport*. Budesamt für Naturschutz. https://www.bfn.de/sites/default/files/BfN/service/Dokumente/skripten/skript113.pdf

BMUV. (2023, January 30). *Politik des BMUV für Nachhaltigkeit im Sport*. https://www.bmuv.de/themen/nachhaltigkeit-digitalisierung/tourismus/politik-des-bmuv-fuer-nachhaltigkeit-im-sport

BMUV Members of the Advisory Board. (2021). *SUSTAINABLE SPORT 2030 – Responsibility for Nature, the Environment and Society*. BMUV Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Tourismus_Sport/positionspapier_nachhaltiger_sport_2030_2112_en_bf.pdf

Bötsch, Y., Tablado, Z., & Jenni, L. (2017). Experimental evidence of human recreational disturbance effects on bird-territory establishment. *Proceedings of the Royal Society B: Biological Sciences*, *284*(1858), 20170846. https://doi.org/10.1098/rspb.2017.0846

Breheny, P., & Burchett, W. (2020). *visreg: Visualization of Regression Models* (2.7.0) [R]. pbreheny.github.io/visreg

Bridge, E. S., & Kelly, J. F. (2013). Reproductive success of belted kingfishers on the upper Hudson River: Hudson River Kingfishers. *Environmental Toxicology and Chemistry*, *32*(8), 1855–1863. https://doi.org/10.1002/etc.2263

Bull, M., & Rödl, T. (2018). Stand Up Paddling (SUP): Eine neue Trendsportart als Problem für überwinternde und rastende Wasservögel? *Berichte zum Vogelschutz*, *55*. https://www.lbv.de/files/user_upload/Dokumente/Projektreporte_Projektskizzen/Stand%20Up%20Paddling/Berichte-zum-Vogelschutz_Bull_R%C3%B6dl-SUP.pdf

Burger, J., & Gochfeld, M. (1991). Human Distance and Birds: Tolerance and Response Distances of Resident and Migrant Species in India. *Environmental Conservation*, *18*(2), 158–165. https://doi.org/10.1017/S0376892900021743

Burger, J., & Gochfeld, M. (1998). Effects of ecotourists on bird behaviour at Loxahatchee National Wildlife Refuge, Florida. *Environmental Conservation*, *25*(1), 13–21. https://doi.org/10.1017/S0376892998000058

Čech, M., & Čech, P. (2015). Non-fish prey in the diet of an exclusive fish-eater: The Common Kingfisher *Alcedo atthis*. *Bird Study*, *62*(4), 457–465. https://doi.org/10.1080/00063657.2015.1073679

Cepková, M., Balážová, M., Melišková, M., & Rubáčová, L. (2022). Influence of age and body condition on breeding performance in Common Kingfisher Alcedo atthis. *Journal of Ornithology*, *163*(1), 251–261. https://doi.org/10.1007/s10336-021-01922-9

Clausen, K. K., Holm, T. E., Pedersen, C. L., Jacobsen, E. M., & Bregnballe, T. (2020). Sharing waters: The impact of recreational kayaking on moulting mute swans Cygnus olor. *Journal of Ornithology*, *161*(2), 469–479. https://doi.org/10.1007/s10336-020-01746-z

Davis, W. J. (1982). Territory Size in Megaceryle Alcyon along a Stream Habitat. *The Auk*, *99*(2), 353–362. JSTOR.

Dougherty, E. M., Vaughn, J. L., & Reichelderfer, C. F. (1975). Characteristics of the non-occluded form of a nuclear polyhedrosis virus. *Intervirology*, *5*(3–4), 109–121. https://doi.org/10.1159/000149889

Ellis, E. C., Gauthier, N., Klein Goldewijk, K., Bliege Bird, R., Boivin, N., Díaz, S., Fuller, D. Q., Gill, J. L., Kaplan, J. O., Kingston, N., Locke, H., McMichael, C. N. H., Ranco, D., Rick, T. C., Shaw, M. R., Stephens, L., Svenning, J.-C., & Watson, J. E. M. (2021). People have shaped most of terrestrial nature for at least 12,000 years. *Proceedings of the National Academy of Sciences*, *118*(17), e2023483118. https://doi.org/10.1073/pnas.2023483118

European Environment Agency. (2019). *Kingfisher—Alcedo Atthis—(Linnaeus, 1758)*. https://eunis.eea.europa.eu/species/Alcedo%20atthis

European Environmental Agency. (2016). *Europe's Environment—The Dobris Assessment 25. Tourism and Recreation*. https://www.eea.europa.eu/publications/92-826-5409-5/page025new.html

European Environmental Agency 2016. (2018). *Population Status and Trends at the EU and Member State Levels*. https://nature-art12.eionet.europa.eu/article12/summary?period=3&subject=Alcedo+atthis&reported_name=

Fontúrbel, F. E., Orellana, J. I., Rodríguez-Gómez, G. B., Tabilo, C. A., & Castaño-Villa, G. J. (2021). Habitat disturbance can alter forest understory bird activity patterns: A regional-scale assessment with camera-traps. *Forest Ecology and Management*, *479*, 118618. https://doi.org/10.1016/j.foreco.2020.118618

Glover, H. K., Guay, P.-J., & Weston, M. A. (2015). Up the creek with a paddle; avian flight distances from canoes versus walkers. *Wetlands Ecology and Management*, *23*(4), 775–778. https://doi.org/10.1007/s11273-015-9411-9

Glover, H. K., Weston, M. A., Maguire, G. S., Miller, K. K., & Christie, B. A. (2011). Towards ecologically meaningful and socially acceptable buffers: Response distances of shorebirds in Victoria, Australia, to human disturbance. *Landscape and Urban Planning*, *103*(3–4), 326–334. https://doi.org/10.1016/j.landurbplan.2011.08.006

González-Oreja, J. A., De La Fuente-Díaz-Ordaz, A. A., Hernández-Santín, L., Bonache-Regidor, C., & Buzo-Franco, D. (2012). Can human disturbance promote nestedness? Songbirds and noise in urban parks as a case study. *Landscape and Urban Planning*, *104*(1), 9–18. https://doi.org/10.1016/j.landurbplan.2011.09.001

Heinzel, H., Fitter, R. S. R., Parslow, J., Hoerschelmann, H., Fitter, R., & Heinzel, H. (1996). *Pareys Vogelbuch: Alle Vögel Europas, Nordafrikas und des Mittleren Ostens ; mit über 3000 Einzeldarstellungen und 600 Verbreitungskarten* (7., vollst. überarb. Aufl). Parey im Blackwell-Wiss.-Verl.

Hlavac, M. (2022). *stargazer: Well-Formatted Regression and Summary Statistics Tables* (5.2.3) [R].

Hockin, D., Ounsted, M., Gorman, M., Hill, D., Keller, V., & Barker, M. A. (1992). Examination of the effects of disturbance on birds with reference to its importance in ecological assessments. *Journal of Environmental Management*, *36*(4), 253–286. https://doi.org/10.1016/S0301-4797(08)80002-3

IPBES. (2019). *Zusammenfassung für politische Entscheidungsträger des globalen Assessments der biologischen Vielfalt und Ökosystemleistungen der Zwischenstaatlichen Plattform für Biodiversität und Ökosystemleistungen*. https://www.de-ipbes.de/files/IPBES%20GA_SPM_DE_2020.pdf

Isotti, R., & Consiglio, C. (n.d.). Activity Rythm at Nest of the Kingfisher, Alcedo Atthis. *Rivista Italiana Di Ornitologia*, *67*(1), 55–59.

Kipping, J. (2018). *Monitoring der Eisvogelbruten am Floßgraben—Brutsaison 2018 Endbericht*. Stadt Leipzig. https://gruenerring-leipzig.de/wp-content/uploads/2020/09/eisvogelmonitoring-flo%C3%9Fgraben-2018.pdf

Klein, M. L., Humphrey, S. R., & Percival, H. F. (1995). Effects of Ecotourism on Distribution of Waterbirds in a Wildlife Refuge. *Conservation Biology*, *9*(6), 1454–1465. https://doi.org/10.1046/j.1523-1739.1995.09061454.x

Knott, J., Mueller, M., Pander, J., & Geist, J. (2020). Seasonal and diurnal variation of downstream fish movement at four small-scale hydropower plants. *Ecology of Freshwater Fish*, *29*(1), 74–88. https://doi.org/10.1111/eff.12489

Laursen, K., Kahlert, J., & Frikke, J. (2005). Factors affecting escape distances of staging waterbirds. *Wildlife Biology*, *11*(1), 13–19. https://doi.org/10.2981/0909-6396(2005)11[13:FAEDOS]2.0.CO;2

Lethlean, H., Van Dongen, W. F. D., Kostoglou, K., Guay, P.-J., & Weston, M. A. (2017). Joggers cause greater avian disturbance than walkers. *Landscape and Urban Planning*, *159*, 42–47. https://doi.org/10.1016/j.landurbplan.2016.08.020

Lüdecke, D., Aust, F., Crawley, S., & Ben-Shachar, M. S. (2023). *ggeffects: Create Tidy Data Frames of Marginal Effects for "ggplot" from Model Outputs* (1.2.0) [R]. strengejacke.github.io/ggeffects/

Lüdecke, D., Bartel, A., Schwemmer, C., Powell, C., Djalovski, A., & Titz, J. (2022). *sjPlot: Data Visualization for Statistics in Social Science* (2.8.12) [R]. strengejacke.github.io/sjPlot/

Lüdecke, D., Makowski, D., Ben-Shachar, M. S., Patil, I., Waggoner, P., Wiernik, B. M., Arel-Bundock, V., Thériault, R., & Jullum, M. (2023). *performance: Assessment of Regression Models Performance* (0.10.2) [R]. easystats.github.io/performance/

MacGregor-Fors, I., & Schondube, J. E. (2011). Gray vs. green urbanization: Relative importance of urban features for urban bird communities. *Basic and Applied Ecology*, *12*(4), 372–381. https://doi.org/10.1016/j.baae.2011.04.003

Mattes, H., & Meyer, E. I. (2001). *Kanusport und Naturschutz- Forschungsbericht über die Auswirkungen des Kanusports an Fließgewässern in NRW*. Institut für Landschaftsökologie & spezielle Zoologie Abt. f. Limnologie der Westfälischen Wilhelms-Universität Münster. https://docplayer.org/73796186-Kanusport-und-naturschutz-forschungsbericht-ueber-die-auswirkungen-des-kanusports-an-fliessgewaessern-in-nrw.html

Méndez Roldán, S. (2013). *Water-Based Recreation Disturbance on Coastal Bird Populations. A Canoeing/Kayaking Case Study in Langstone Harbour, UK* [University of Portsmouth]. http://www.solentems.org.uk/natural_environment_group/NEG_Projects/Water-based%20recreation%20disturbance%20on%20coastal%20bird%20populations-%20A%20canoeing-kayaking%20case%20study%20in%20Langstone%20Harbour.pdf

Parslow, J. (1996). *Pareys Vogelbuch: Alle Vögel Europas, Nordafrikas und des Mittleren Ostens: mit über 3000 Einzeldarstellungen und 600 Verbreitungskarten* (7., vollst. überarb. Aufl). Parey.

Platteeuw, M., & Henkens, R. J. H. G. (1997). Possible Impacts of Disturbance to Waterbirds: Individuals, Carrying Capacity and Populations. *Wildfowl*, *48*(48), 225–236.

R Core Team. (2021). *R: A Language and Environment for Statistical Computing* [R]. R Foundation for Statistical Computing. https://www.R-project.org/

Ramankutty, N., Mehrabi, Z., Waha, K., Jarvis, L., Kremen, C., Herrero, M., & Rieseberg, L. H. (2018). Trends in Global Agricultural Land Use: Implications for Environmental Health and Food Security. *Annual Review of Plant Biology*, *69*(1), 789–815. https://doi.org/10.1146/annurev-arplant-042817-040256

Raven, P. (1986). The size of minnow prey in the diet of young Kingfishers *Alcedo atthis*. *Bird Study*, *33*(1), 6–11. https://doi.org/10.1080/00063658609476884

Reichholf, J. H. (1998). *Kanuwandersport und Naturschutz- Ein lösbarer Konflikt?- Untersuchungen im Auftrag des Deutschen Kanu Verbandes e.v.* Deutscher Kanuverband e.V. file:///C:/Users/bt306529/Downloads/1509650567-Kanuwandersport-und-Naturschutz.pdf

Reichholf, J. H. (2001). *Störungsökologie: Ursache und Wirkung von Störungen*. Bayerische Akademie für Naturschutz und Landschaftspflege (ANL).

Roth, R., Türk, S., & Klos, G. (n.d.). *Umwelt, Naturschutz Und Sport Im Dialog*. Bundesamt für Naturschutz. https://www.dshs-koeln.de/fileadmin/redaktion/Institute/Natursport_und_Oekologie/Veroeffentlichungen/Schriftenreihe/INOEK_Band_17_Kongressbericht_2004.pdf

Ryslavy, T., Bauer, H.-G., Gerlach, B., Hüppop, O., Stahmer, J., Südbeck, P., & Sudfeldt, C. (2020). Rote Liste der Brutvögel Deutschlands (6. Edition). *Berichte zum Vogelschutz*, 13–112.

Schafft, M., Wegner, B., Meyer, N., Wolter, C., & Arlinghaus, R. (2021). Ecological impacts of water-based recreational activities on freshwater ecosystems: A global meta-analysis. *Proceedings of the Royal Society B: Biological Sciences*, *288*(1959), 20211623. https://doi.org/10.1098/rspb.2021.1623

Schorr, M. (2000). Störungsökologische Wirkungen von Bootsportaktivitäten auf Fließgewässer-Libellen—Dargestellt am Beispiel der Wieslauter (Pfälzerwald, Rheinland-Pfalz. *Fauna Flora Rheinland-Pfalz*, *9*(2), 663–679.

Spinu, V., Grolemund, G., Wickham, H., Vaughan, D., Lyttle, I., Costigan, I., Law, J., Mitarotonda, D., Larmarange, J., Boiser, J., & Hee Lee, C. (2023). *lubridate: Make Dealing with Dates a Little Easier* (1.9.2) [R]. github.com/tidyverse/lubridate

Stasko, A. D., Patenaude, T., Strecker, A. L., & Arnott, S. E. (2012). Portage connectivity does not predict establishment success of canoe-mediated dispersal for crustacean zooplankton. *Aquatic Ecology*, *46*(1), 9–24. https://doi.org/10.1007/s10452-011-9378-4

Stott, T. (2019). Water Sports and Water-Based Recreation. In D. Huddart & T. Stott, *Outdoor Recreation* (pp. 331–359). Springer International Publishing. https://doi.org/10.1007/978-3-319-97758-4_13

Suri, J., Anderson, P. M., Charles-Dominique, T., Hellard, E., & Cumming, G. S. (2017). More than just a corridor: A suburban river catchment enhances bird functional diversity. *Landscape and Urban Planning*, *157*, 331–342. https://doi.org/10.1016/j.landurbplan.2016.07.013

Tablado, Z., & Jenni, L. (2017). Determinants of uncertainty in wildlife responses to human disturbance: Modulators of wildlife response to recreation. *Biological Reviews*, *92*(1), 216–233. https://doi.org/10.1111/brv.12224

Thiel, D., Jenni-Eiermann, S., & Jenni, L. (2008). Der Einfluss von Freizeitaktivitäten auf das Fluchtverhalten, die Raumnutzung und die Stressphysiologie des Auerhuhns Tetrao urogallus. *Der Ornithologische Beobachter*, *105*(1). https://www.ala-schweiz.ch/images/stories/pdf/ob/2008_105/OrnitholBeob_2008_105_85_Thiel.pdf

Tuite, C. H., Hanson, P. R., & Owen, M. (1984). Some Ecological Factors Affecting Winter Wildfowl Distribution on Inland Waters in England and Wales, and the Influence of Water-Based Recreation. *The Journal of Applied Ecology*, *21*(1), 41. https://doi.org/10.2307/2403036

Türk, S., Jakob, E., Krämer, A., & Roth, R. (2004). *Outdoor recreation activities in nature protection areas – situation in Germany*. *2*, 171–177.

United Nations, Departments of Economic and Social Affairs, Population Division. (2019). *World population prospects 2019: Highlights*. United Nations.

Venohr, M., Langhans, S. D., Peters, O., Hölker, F., Arlinghaus, R., Mitchell, L., & Wolter, C. (2018). The underestimated dynamics and impacts of water-based recreational activities on freshwater ecosystems. *Environmental Reviews*, *26*(2), 199–213. https://doi.org/10.1139/er-2017-0024

Vilches, A., Arizaga, J., Miranda, R., & Ibbotson, A. (2013). Impact of Common Kingfisher on a salmon population during the nestling period in southern England. *Knowledge and Management of Aquatic Ecosystems*, *410*, 03. https://doi.org/10.1051/kmae/2013058

Warnes, G. R., Bolker, B., Gorjanc, G., Grothendieck, G., Korosec, A., Lumley, T., MacQueen, D., Magnusson, A., & Rogers, J. (2022). *gdata: Various R Programming Tools for Data Manipulation* (2.18.0.1) [R].

Wickham, H., François, R., Henry, L., Müller, K., & Vaughan, D. (2023). *dplyr: A Grammar of Data Manipulation* (1.1.0) [R]. dplyr.tidyverse.org

Wickham, H., & RStudio. (2023). *tidyverse: Easily Install and Load the "Tidyverse"* (2.0.0) [R]. github.com/tidyverse/tidyverse

Wüst, W. (1986). *Avifauna Bavariae—Die Vogelwelt Bayerns im Wandel der Zeit* (1st ed.). Gebrüder Geiselberger.

Zauner, G., & Ratschan, C. (2004). *Auswirkungen des Kanusports auf die Fischfauna*. Studie im Auftrag des Deutschen Kanuverbandes e. V. file:///C:/Users/bt306529/Downloads/1489943154-Studie-zu-den-Auswirkungen-des-Kanusports-auf-die-Fischfauna.pdf

Zhang, W., Shi, J., Huang, H., & Liu, T. (2017). The impact of disturbance from photographers on the Blue-crowned Laughingthrush (Garrulax courtoisi). *Avian Conservation and Ecology*, *12*(1), art15. https://doi.org/10.5751/ACE-01007-120115

Manuscript 4 - Overcoming the challenge of remotely monitoring small birds using video traps and artificial intelligence: An example with the common kingfisher *Alcedo atthis*

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Abstract

In the light of technological advances, video trapping has become a practical and feasible method for wildlife monitoring. This method can be used completely off the grid, using solar power and cellular networks. Entry-level machine learning skills are sufficient to develop a bespoke AI to identify events at the study site. For the setup in the field and the data analysis, consumer grade equipment is adequate. In ecological applications, it is possible to combine video trapping data sets with other data gathered by other methods. In this paper, we use a combination of video data of common kingfisher *Alcedo atthis* at their nest and camera trap data of outdoor activities on the river in front of the bird's nest. Our video trap recorded a total of 580 hours of footage. The AI trained for our study achieves an equalerror rate of 2.4%, and allowed us to identify 6345 common kingfisher events. In future work, it is possible to quantify the impact of outdoor activities on the river segment adjacent to the nest on the common kingfisher's presence. Moreover, given the relative simplicity of our setup, an extension to more sites and longer deployments is conceivable.

Keywords: birds, canoeing, kayaking, remote sensing, SUPs, CCTV, machine learning, computer vision, sports ecology

Introduction

For assessing the effects of human activity on wildlife, minimally intrusive automated methods that do not require an observer present at location are most practical (Rowcliffe & Carbone 2008, Rowcliffe et al. 2011, Meek & Vernes 2016). Video trapping is a common method for monitoring biodiversity, either through continuous recording, at scheduled intervals, or triggered by specific events. This is done either from a fixed position or animal-borne, i.e. attached to an organism (Rutz & Troscianko 2013, Moll et al. 2007). Video trapping is less common than camera trapping due to the elaborate and expensive equipment needed and the logistical challenge to set it up in the field (Young 2016, Juneau et al. 2017). With technological advances, like smaller devices and the ability to upload data immediately to a cloud instead of storing it on a device at location, its application is getting more feasible to use this method. Continuous video trapping does not rely on motion triggers or heat signatures and hence avoids a number of pitfalls camera trapping carries. Factors affecting the efficiency of movement triggers in camera traps are light conditions, temperature and the innate trigger time of the camera (Swann et al 2004, Welborne 2014, Hamel et al 2013). Additionally, small animals are less likely to trigger a camera trap (Kelly 2008, Anile & Devillard 2016, Urlus et al. 2014), with some ectothermic animals not triggering at all (Pegoraro et al. 2020). Jumeau et al (2017) compared video trap data with camera trap data and found that the latter missed 44% of small and 17% of medium-sized mammal events. Furthermore, detection probability is influenced by the direction of the observed animal's approach, with a parallel approach being detected more reliably than a frontal approach (Randler & Kalb 2018). Another method of assessing wildlife is biologging via tags, which can have one or more technology on board, e.g. VHF, GPS, accelerometer, gyroscope or temperature sensor. Tags are used to gather data on physiology, location and behaviour of wild animals (Cooke et al. 2004, Hooker et al. 2007, Ropert-Coudert et al. 2009), but oftentimes require elaborate calibration and cross-validation (Rutz & Troscianko 2013). Furthermore, attaching tags requires capturing them and falls into the category of animal experimentation, requiring authorization. Tags can also interfere with the animal's well-being or behaviour (Hawkins 2004, Wilson & McMahon 2006, McMahon et al. 2008). For the method of video tracking, miniature video cameras are mounted on birds similarly to tags (Bluff & Rutz 2008). This can eliminate the need for cross-validation, since the video provides a direct record (Rutz & Troscianko 2013).

In our study, we use breeding pairs of the small bird common kingfisher *Alcedo atthis* as an example to demonstrate the efficiency of video traps to quantify possible effects of human presence on feeding behaviour. Common kingfishers are small birds, measuring 16-18 cm in height and a wingspan of 25 cm (Fry & Fry 1999). They are plunge divers and feed on fish, insects and amphibians (Bezzel 1985, Raven 1986,Wüst 1986, Heinzel et al. 1996, Čech & Čech 2015). For breeding purposes, most times they dig a burrow into a suitable escarpment right next to a body of water (Bezzel 1985). After hatching, the parents bring food items into the burrow to feed the nestlings for about 24-25 days (Fry & Fry 1999). Near the burrow, parents choose a regular perching place to observe, rest and preen. A parent carrying a food item will often pause on the perch before entering its burrow (Heinzel et al. 1996). Common kingfishers have used the studies nesting site for several consecutive years and their preferred perch was known to be right in front of the nest entrance, which is why we could observe the nest entrance and the perch in the same frame setup. Although common kingfishers are classified globally (IUCN 2020) and in Europe (IUCN 2016) as least concern, in Germany it is a rigorously protected species by law (see *§§ 7 Abs.2 Nr.14 lt. c), 54 Abs.2 Bundesnaturschutzgesetz* and *§ 1 Satz 2 Bundesartenschutzverordnung*).

The aim of this study was to observe the bird's activity at its nest continuously. A core challenge of video trapping, when recording continuously without a trigger, is the volume of the resulting data. Data transfer and storage can be a concern depending on the recording settings, but modern mobile bandwidth and the commercial availability of terabyte-scale storage render this challenge conquerable. Manual review of the data is oftentimes not feasible, thus automated methods of identifying relevant events should be used (Weinstein 2015).

Machine learning for computer vision, colloquially called artificial intelligence (AI), has made tremendous progress in the past decade. As tools and methods evolve, building machine learning pipelines for standard tasks becomes easier and requires less specialist knowledge. Paired with the feasibility of running training and inference of an AI on consumer-grade computer hardware, this technology can be applied widely. There are fully trained machine learning solutions available, built to classify images recorded by camera traps, e.g., the Megadetector (Beery et al. 2019). Unfortunately, they do not easily generalize to very different setups such as the one used in our study. As AI solutions do not generalize easily, bespoke solutions for specific datasets are needed. Such bespoke computer vision models have already been applied in ecological studies, e.g., in species diversity monitoring of nocturnal insects (Korsch et al. 2023).

Simultaneously to video trapping, other sensors can be deployed. This yields multiple datasets which can be correlated and thus allow the study of interactions. As an example, we used camera traps to observe outdoor activities on the river segment in front of the video trapped common kingfisher nest.

In our study, we demonstrate the feasibility of deploying video traps in the field. Our setup is powered locally and transmits data using cellular networks, which means no power or network grid is required on-site. A bespoke AI is trained for the recorded video dataset and used to identify times of common kingfisher presence. We qualitatively show a prospective application in ecology by relating our video data results to camera trap recordings of human activity close by.

Methods

The aim of this study was to observe the bird's activity at a common kingfisher (*Alcedo atthis*) nest continuously. This might serve as a proxy for feeding activity during breeding season and rearing of the nestlings. We conducted our study at a tall escarpment at the river Regnitz, about 7 km south of the town Bamberg, Bavaria, Germany. The escarpment is part of a small hedgerow that is marked with a no trespassing sign. On one side, the hedgerow borders on a small beach used for recreation. On the other side, it borders on a meadow used for sunbathing and a dirt road used for promenading and biking. Common kingfisher and other bird species have used the escarpment for several consecutive years as a nesting site.

The setup in the field consisted of a web-enabled 4G LTE PTZ dome camera (P5066-22 by AP), a car battery with a capacity of 61 Ah, two solar panels with a maximum power of 80 W each to keep the battery topped off and a weatherproof box containing the connecting electronics and timer (see figure 1, B & C). We propped up the solar panels at a 45° angle, with the car battery placed under one of the panels for shelter. We mounted the video camera and box on a board, which we attached to a pole with view of the nesting site. The video camera contained a SIM-Card and had access to the internet. It is able to turn on three axis, which allowed to adjust its view of the nesting site remotely from the lab, after the setup in the field was complete. We saved the live feed on a lab computer in 5-minutes increments and then split it into frames to train our KI. We filmed from 17th May 2022 to 14th June 2022 from right before sunrise until shortly after sundown, resulting 16,677,876 frames.

The machine learning task was framed as a frame-wise binary classification, with the presence of a common kingfisher as the positive class and the absence of a common kingfisher as the negative class. We labelled 90 of the recorded 5-minute sequences by hand using the online tool Make Sense (Skalski 2019), yielding a total of 244,200 annotated frames. Of these, 5,833 frames from 21 distinct 5-minute sequences showed presence of a common kingfisher. We used only sequences with at least one positive class frame in training the algorithms, to reduce the class imbalance and resulting in a dataset of 50,056 frames. We cropped the frames to a region of interest (see figure 1, A), which covers the preferred perching location, nest entrance and common flight path of the observed birds. This step was crucial in successfully training the machine learning algorithms, preventing data leakage through the metadata included in the title bar at the top of the recorded frames, as well as increasing the relative fraction of relevant pixels for the classification. We trained the model using open-source framework TensorFlow (TensorFlow 2023). The model used for the classification is an EfficientNet V2 B0 model (Tan & Le 2021), using pre-trained weights as provided in the TensorFlow Keras applications library. For training, we used four-fold cross-validation. We split the dataset into folds by recording sequence to avoid data leakage. Five folds were separated, using one as a hold-out set across all cross-validation steps, to enable unbiased evaluation of the results. Each training run lasted for 15 epochs, keeping the EfficientNet backbone frozen for the first four epochs. Optimization was done using the AdamW algorithm as implemented in Keras, with an initial learning rate of $5*10^{-4}$, that was halved every epoch after the fifth. We combined four models from one run of cross-validation into an ensemble, using the average of the model scores as the ensemble's output. Inference of the ensemble was conducted on consumer-grade hardware (CPU Intel i5 at 4x3.4 GHz, GPU NVidia GTX 1070), and ran at ~100 frames / second.

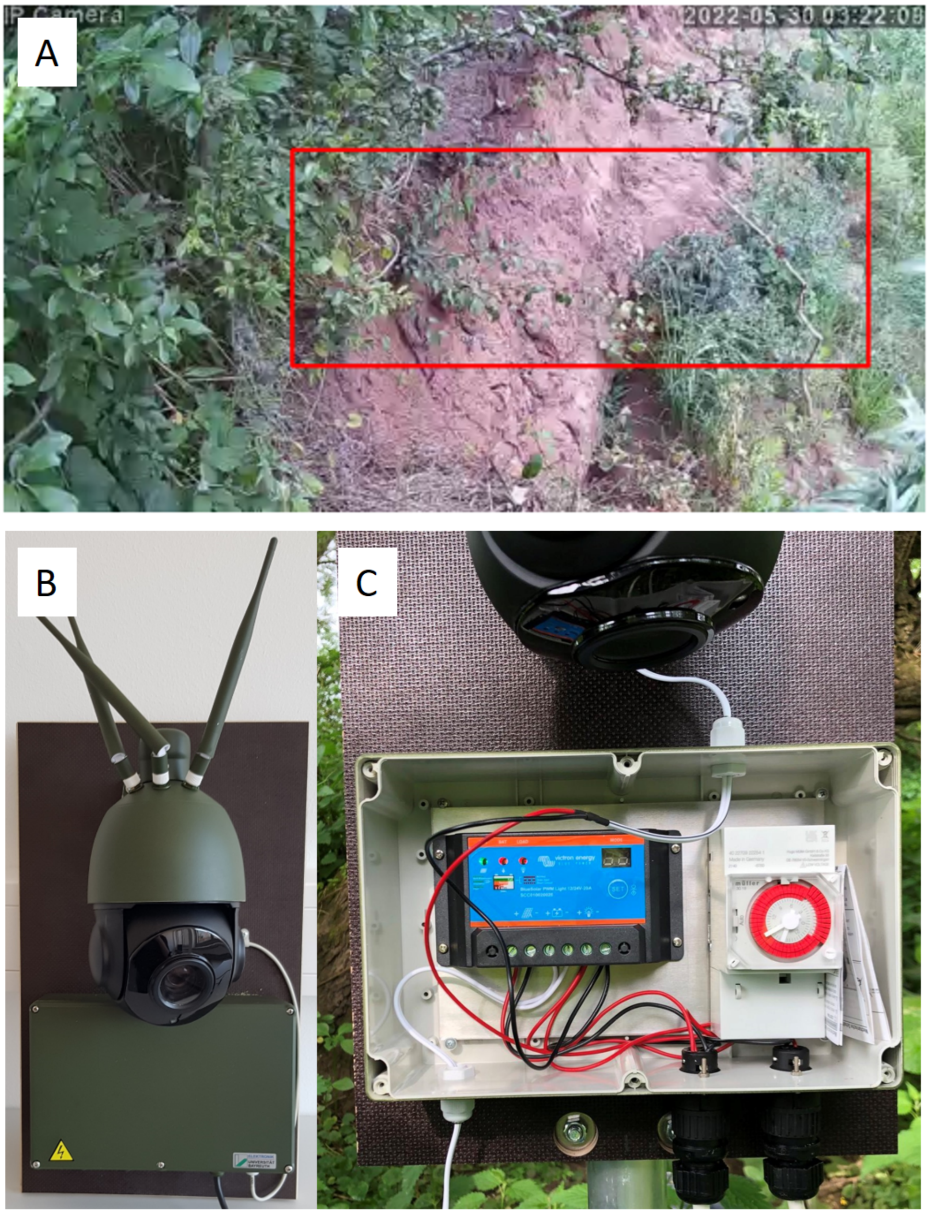

Figure 1: Pictures of the study site and equipment used. Picture A shows an example frame with a kingfisher perching on a branch on the right of the image. The region of interest is marked in red. It includes the kingfisher's preferred perching spot as well as the nest entrance. Picture B shows the dome camera used for the study. Picture C shows the connecting electronics inside the weatherproof box.

Software used in the development process was Python 3.9.16 (van Rossum & Drake 2009), tensorflow (TensorFlow 2023), numpy (Harris et al. 2020) and pandas (Pandas Development Team 2020, McKinney 2010).

As an example of combination of data sets with video data, we mounted a regular camera trap (HF2X HyperFire 2 by Reconyx) on a nearby tree at the nesting site. The camera observed the segment of the river Regnitz in front of the videotrapped common kingfisher nest, and thus exerted recreational activities, mainly paddling activities like canoeing or stand-up paddling. We setup the camera trap with the default settings (3 pictures per trigger, 1 s pause between pictures, no delay between triggers) and blurred the lens with a filter to protect people's privacy. At the nearest access sites for paddling activities, we mounted signs indicating camera traps in the area. We categorized the resulting photos and plotted them and the identified common kingfisher events on a timeline.

Results

We captured 580 hours of video, a total of 16,677,876 frames, at a nesting site of common kingfisher *Alcedo atthis*. Of these, we labelled 244,200 frames by hand to train and evaluate bespoke computer vision models. The selection of a static region of interest within the frames is the only site-specific step taken in the development of the model - this can be seen as a post-hoc adjustment of the camera setup. Using cross-validation, we built an ensemble of models to yield a more stable classifier. The ensemble achieves an equal error rate of 2.1%, meaning it can classify individual frames with an equal 2.1% rate of false positive and false negative results. To identify presence of common kingfishers, we selected a working point with a set false positive rate of 0.2% and a false negative rate of 3.2%. Figure 2 shows the model's detection error trade-off with the equal error point and our chosen working point marked.

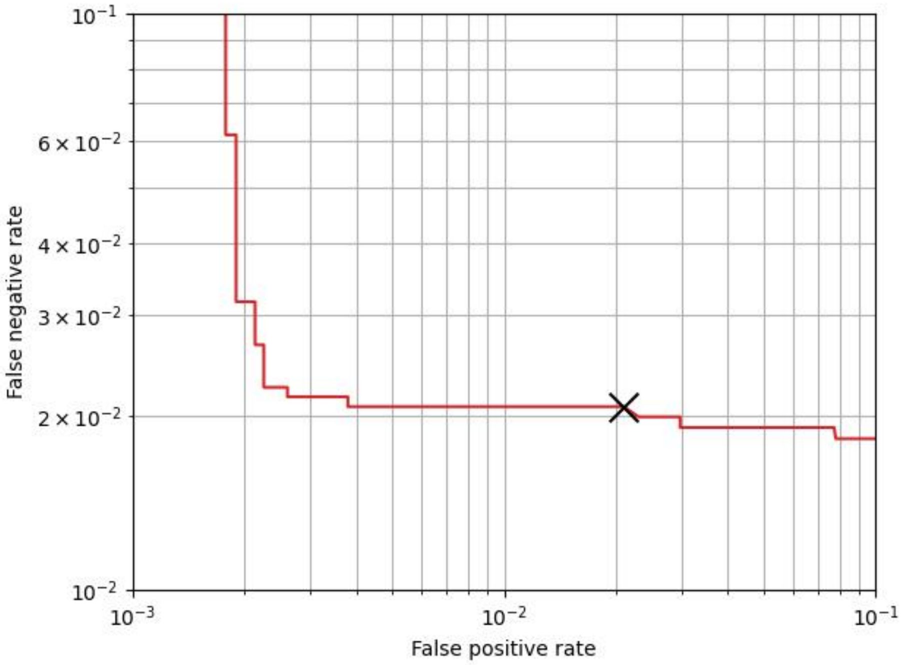

Figure 2: Detection error trade-off for the ensemble built. The red line indicates possible trade-offs of model errors for different values of the decision threshold. The equal error point is marked with a cross.

We considered all frames with a model score above the threshold of 0.3 as a confident common kingfisher indicator; all other frames were considered empty. We compared the model results with our hand labelled results, using a holdout data set that was not used for model training. This places each frame in one of four categories: true positive with the model correctly indicating a common kingfisher, false negative with the model incorrectly indicating no bird, true negative with the model correctly indicating no bird, and false positive with the model incorrectly indicating a common kingfisher (see figure 3 and figure 4). It is important to interpret the models output in context. While predictions are frame-wise, we are interested in events, meaning periods of common kingfisher presence. In order to group frames into events, we decided that an event consists of one or more kingfisher frames, with consecutive common kingfisher detections being no more than 5 seconds apart. Figure 3 shows model predictions in context of events.

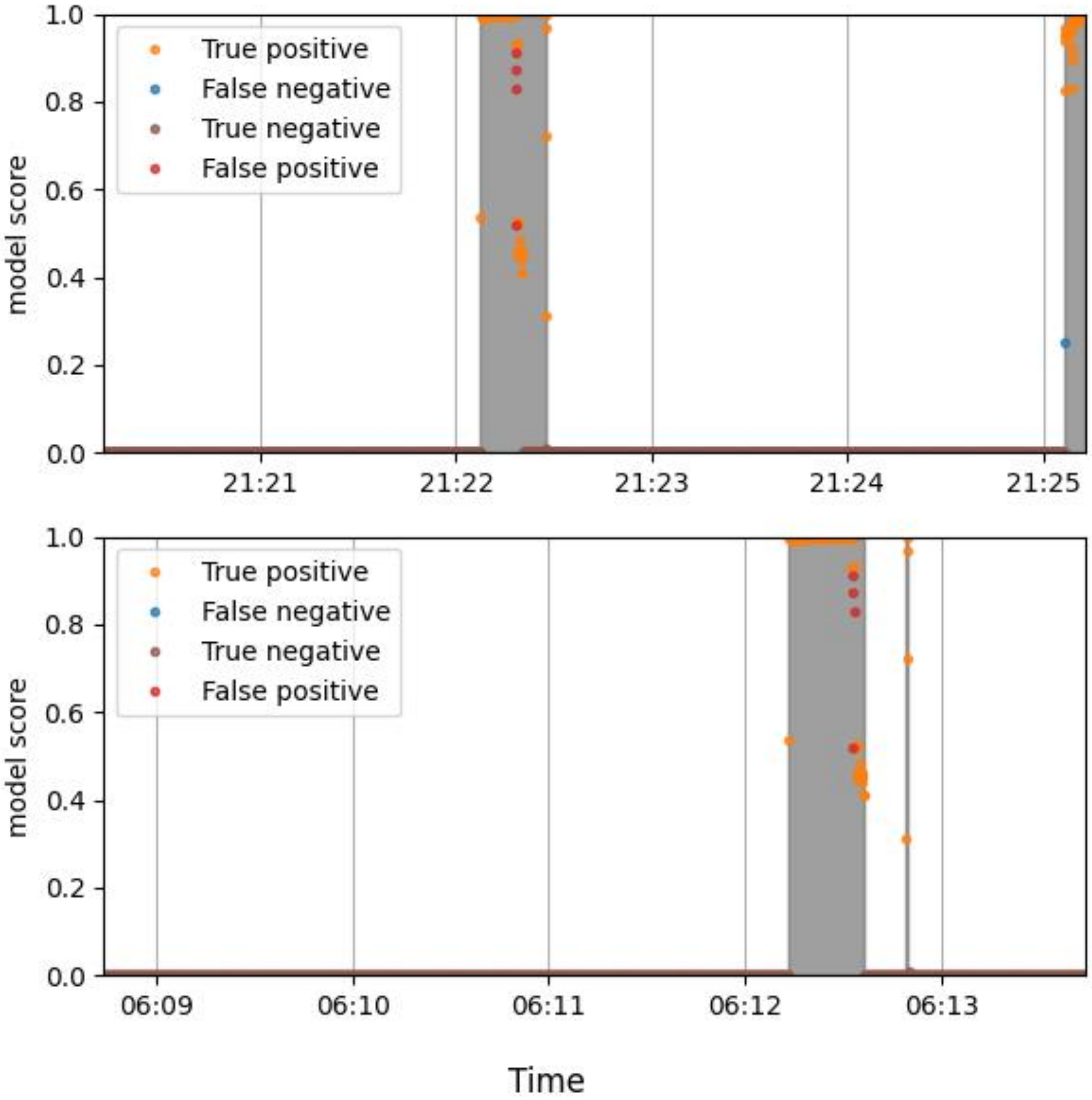

Figure 3: Visualization of model predictions on hold-out set frames for two selected examples. Points indicate the model score for individual frames, with their colour indicating their category. Event are marked in grey.

Figure 4: Examples of frames from all four categories of model predictions. All pictures show the area of interest of the model used. A = true positive, B = false negative, C = true negative, D = false positive.

We identified a total of 6,345 events, amounting to a common kingfisher presence of 30.8 hours (see figure 5). The median duration of a common kingfisher event is 4.5 seconds. We found three events lasting more than half an hour. On closer inspection, they were identified to be systematic errors, e.g. due to foliage temporarily covering a part of the camera's field of view, and thus were removed from the data set.

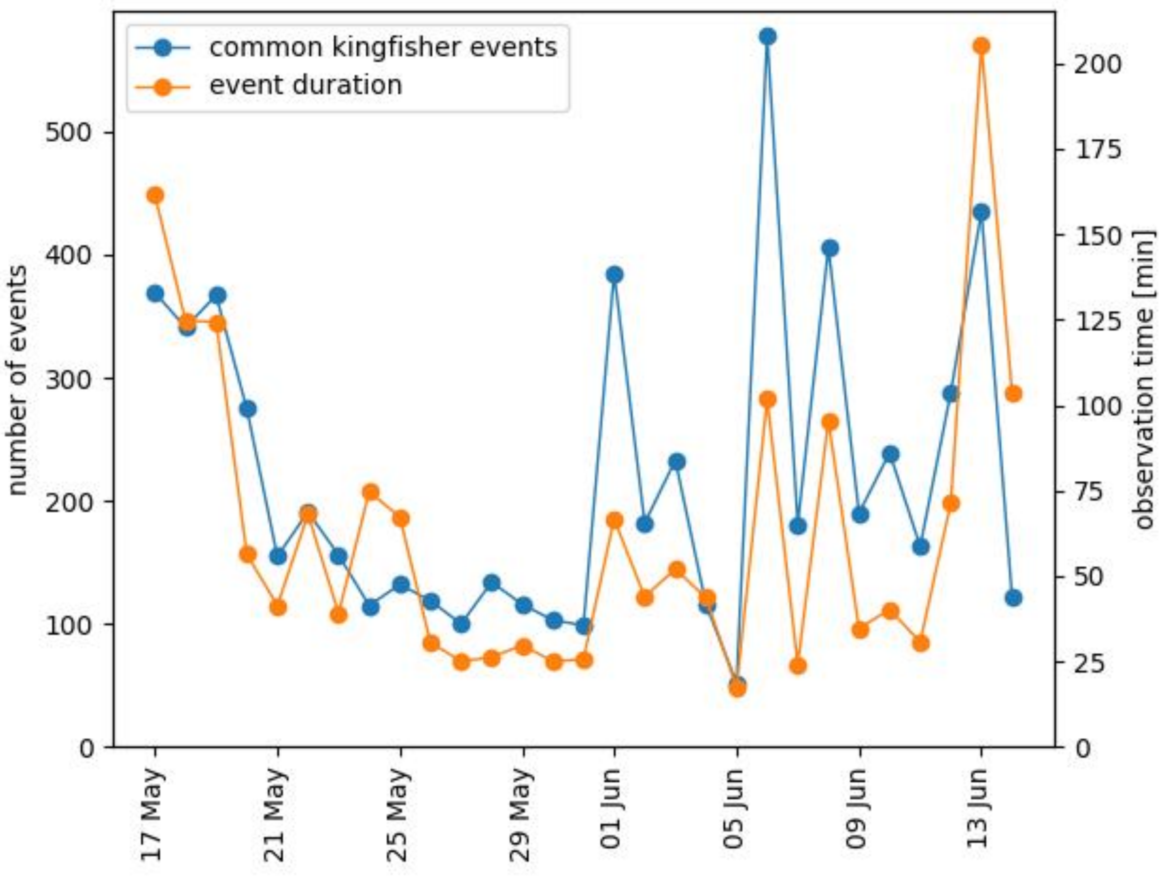

Figure 5: Common kingfisher events and sum of their durations for every day of the study period.

For our example of combining data sets, we visualised common kingfisher events together with outdoor activity events, in this case canoeing and SUPing (see figure 6). This kind of juxtaposition allows statistical methods to be applied, e.g. correlation analysis. However, a formal statistical analysis of both data sets is outside the scope of this paper.

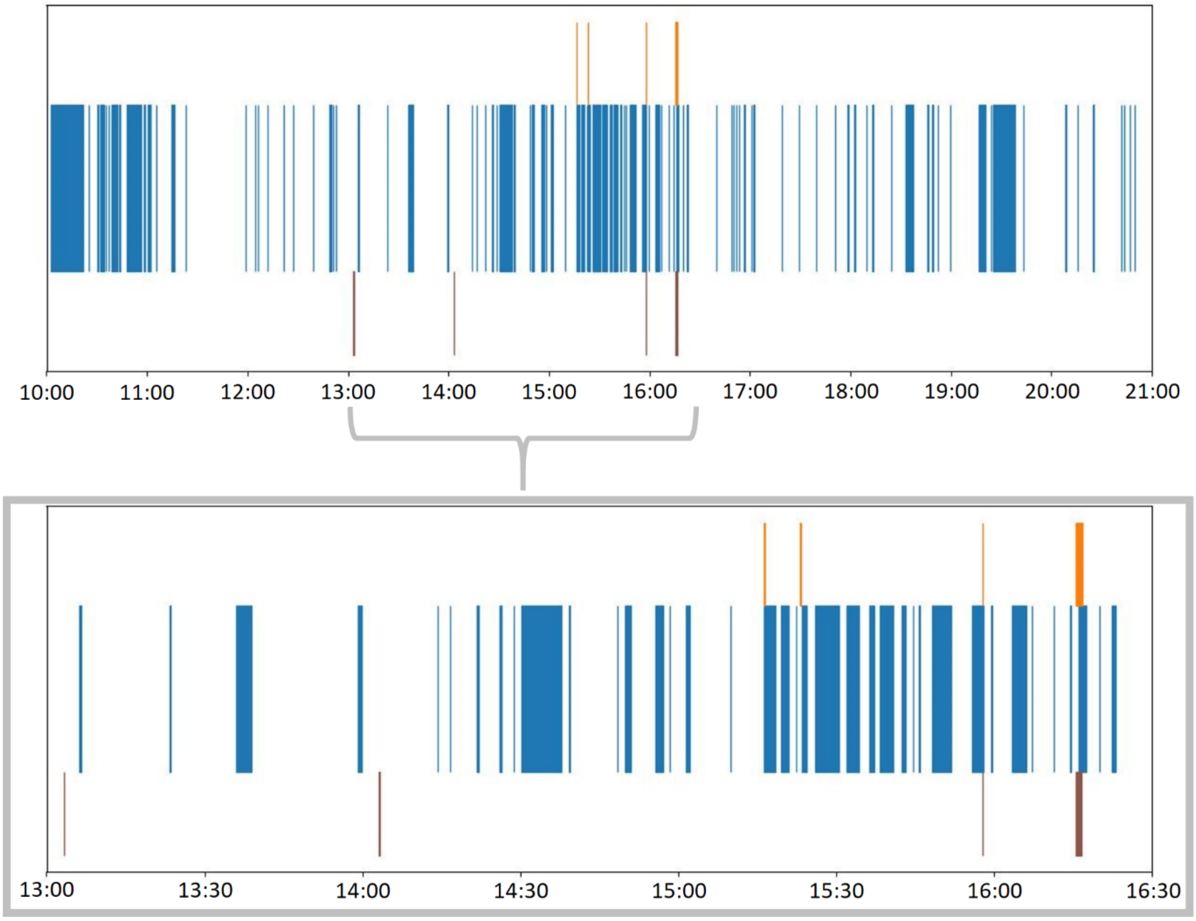

Figure 6: Visualisation of both camera and video data from 22nd of May 2022. The lower part of the graphic zooms into the indicated region. The coloured bars indicate the duration of common kingfisher and outdoor activity events. Orange = SUP events, blue = common kingfisher events, brown = canoe events.

Discussion

In this study, we showed that remote monitoring using video traps is feasible and can be used where other methods fall short, e.g. for small birds like the common kingfisher *Alcedo atthis*. Video traps are minimally invasive and are very reliable since they do record continuously instead of relying on a trigger. Individually tagging the observed birds would have been expensive, stressful for the birds and overshot our goal of observing the nesting site. Camera traps would have likely not been able to detect the bird reliably due to its size (Kelly 2008, Anile & Devillard 2016, Urlus et al. 2014) and speed (Rowliffe et al. 2011, Jumeau et al. 2017). According to Randler & Kalb (2018), we would have needed to mount camera traps at most 1.2m away from the nest entrance for a trigger percentage of ~50%. In our study, this would have interfered massively with the habitat and potentially negatively affected the birds.

A big challenge when deploying video traps is the amount of data gathered. We overcame this with a bespoke AI, tailored to the study site. The AI in this study was able to detect presence or absence of common kingfisher. We then grouped frames with common kingfishers present into events. These events can contain birds entering or exiting the nest, or both when in quick succession. They also contain birds perching and displaying various behaviour, e.g. preening, waiting for partner, luring offspring. The number and duration of common kingfisher observations close to its nest are already highly valuable ecological information, which would require a lot of effort to obtain otherwise. Given the reduced time investment when using video traps, long-term studies and comparisons year-over-year are feasible. With this, subtle changes can be made visible, e.g. in common kingfisher behaviour.

We see great potential in a more sophisticated automatic classification of displayed bird behaviour, which could automatically count entries and exists, time spend inside the nest and time spent perching. Creating a more complex AI will require deeper knowledge and more time, which makes it less feasible for non-specialists. It also makes the creation of a bespoke AI for each site significantly more costly. Another opportunity for improvement is more sophisticated camera equipment, e.g. enhanced resolution. Eventually, this can enable detection of more discreet behaviour like viewing direction and beak position, or type and quality of food items. It would then be possible to infer the actual feeding activity over time.

In the context of ecological questions, we showed that it is easily possible to correlate results of video trapping to other data sets, as we did with the presence of kingfishers and nearby human activity. Since we used basic and standard methods to develop the AI, it is feasible to train a custom video frame classified with entry-level knowledge. With the combination of video trapping and AI, it is possible to study species where other methods fall short - as long as the subject repeatedly visits a specific site, e.g. a crossing, feeding ground or nesting place.

Statements and Declarations

Competing Interest: The authors declare no conflict of interest.

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Data Availability Statement: The scripts and models used are available at https://github.com/neuneck/kingfisher_bt

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References

Anile, S., & Devillard, S. (2016). Study design and body mass influence RAIs from camera trap studies: Evidence from the Felidae: Factors affecting camera-trapping success rate across felids. *Animal Conservation*, *19*(1), 35–45. https://doi.org/10.1111/acv.12214

Beery, S., Morris, D., & Yang, S. (2019). *Efficient Pipeline for Camera Trap Image Review*. https://doi.org/10.48550/ARXIV.1907.06772

Bezzel, E. (1985). *Kompendium der Vögel Mitteleuropas—Nonpasserieformes* (1st ed.). Aula Verlag.

Bluff, L. A., & Rutz, C. (2008). A quick guide to video-tracking birds. *Biology Letters*, *4*(4), 319–322. https://doi.org/10.1098/rsbl.2008.0075

Čech, M., & Čech, P. (2015). Non-fish prey in the diet of an exclusive fish-eater: The Common Kingfisher *Alcedo atthis*. *Bird Study*, *62*(4), 457–465. https://doi.org/10.1080/00063657.2015.1073679

Cooke, S. J., Hinch, S. G., Wikelski, M., Andrews, R. D., Kuchel, L. J., Wolcott, T. G., & Butler, P. J. (2004). Biotelemetry: A mechanistic approach to ecology. *Trends in Ecology & Evolution*, *19*(6), 334–343. https://doi.org/10.1016/j.tree.2004.04.003

Fry, C. H., & Fry, K. (1999). *Kingfishers, bee-eaters & rollers: A handbook* (1. publ). Helm.

Hamel, S., Killengreen, S. T., Henden, J.-A., Eide, N. E., Roed-Eriksen, L., Ims, R. A., & Yoccoz, N. G. (2013). Towards good practice guidance in using camera-traps in ecology: Influence of sampling design on validity of ecological inferences. *Methods in Ecology and Evolution*, *4*(2), 105–113. https://doi.org/10.1111/j.2041-210x.2012.00262.x

Harris, C. R., Millman, K. J., Van Der Walt, S. J., Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., Van Kerkwijk, M. H., Brett, M., Haldane, A., Del Río, J. F., Wiebe, M., Peterson, P., … Oliphant, T. E. (2020). Array programming with NumPy. *Nature*, *585*(7825), 357–362. https://doi.org/10.1038/s41586-020-2649-2

Hawkins, P. (2004). Bio-logging and anial welfare: Practical refinements. *Mem Natl Inst Polar Res*, *58 (Special Issue)*, 58–68.

Heinzel, H., Fitter, R. S. R., Parslow, J., Hoerschelmann, H., Fitter, R., & Heinzel, H. (1996). *Pareys Vogelbuch: Alle Vögel Europas, Nordafrikas und des Mittleren Ostens ; mit über 3000 Einzeldarstellungen und 600 Verbreitungskarten* (7., vollst. überarb. Aufl). Parey im Blackwell-Wiss.-Verl.

Hooker, S. K., Biuw, M., McConnell, B. J., Miller, P. J. O., & Sparling, C. E. (2007). Bio-logging science: Logging and relaying physical and biological data using animal-attached tags. *Deep Sea Research Part II: Topical Studies in Oceanography*, *54*(3–4), 177–182. https://doi.org/10.1016/j.dsr2.2007.01.001

IUCN. (2016). *Alcedo atthis: BirdLife International: The IUCN Red List of Threatened Species 2016: e.T22683027A89575948* [dataset]. https://doi.org/10.2305/IUCN.UK.2016-3.RLTS.T22683027A89575948.en

IUCN. (2020). *Alcedo atthis: BirdLife International: The IUCN Red List of Threatened Species 2021: e.T22683027A166217110* [dataset]. https://doi.org/10.2305/IUCN.UK.2021-3.RLTS.T22683027A166217110.en

Jumeau, J., Petrod, L., & Handrich, Y. (2017). A comparison of camera trap and permanent recording video camera efficiency in wildlife underpasses. *Ecology and Evolution*, *7*(18), 7399–7407. https://doi.org/10.1002/ece3.3149

Kelly, M. J. (2008). Design, evaluate, refine: Camera trap studies for elusive species. *Animal Conservation*, *11*(3), 182–184. https://doi.org/10.1111/j.1469-1795.2008.00179.x

Korsch, D., Bodesheim, P., Brehm, G., & Denzler, J. (2023). *Automated Visual Monitoring of Nocturnal Insects with Light-based Camera Traps*. https://doi.org/10.48550/ARXIV.2307.15433

McKinney, W. (2010). *Data Structures for Statistical Computing in Python*. 56–61. https://doi.org/10.25080/Majora-92bf1922-00a

McMahon, C. R., Field, I. C., Bradshaw, C. J. A., White, G. C., & Hindell, M. A. (2008). Tracking and data–logging devices attached to elephant seals do not affect individual mass gain or survival. *Journal of Experimental Marine Biology and Ecology*, *360*(2), 71–77. https://doi.org/10.1016/j.jembe.2008.03.012

Meek, P. D., & Vernes, K. (2016). Can camera trapping be used to accurately survey and monitor the Hastings River mouse (Pseudomys oralis)? *Australian Mammalogy*, *38*(1), 44. https://doi.org/10.1071/AM15016

Moll, R. J., Millspaugh, J. J., Beringer, J., Sartwell, J., & He, Z. (2007). A new 'view' of ecology and conservation through animal-borne video systems. *Trends in Ecology & Evolution*, *22*(12), 660–668. https://doi.org/10.1016/j.tree.2007.09.007

Pandas Development Team. (2023). *pandas-dev/pandas: Pandas* (v2.1.0rc0) [Computer software]. Zenodo. https://doi.org/10.5281/ZENODO.3509134

Pegoraro, L., Hidalgo, O., Leitch, I. J., Pellicer, J., & Barlow, S. E. (2020). Automated video monitoring of insect pollinators in the field. *Emerging Topics in Life Sciences*, *4*(1), 87–97. https://doi.org/10.1042/ETLS20190074

Randler, C., & Kalb, N. (2018). Distance and size matters: A comparison of six wildlife camera traps and their usefulness for wild birds. *Ecology and Evolution*, *8*(14), 7151–7163. https://doi.org/10.1002/ece3.4240

Raven, P. (1986). The size of minnow prey in the diet of young Kingfishers *Alcedo atthis*. *Bird Study*, *33*(1), 6–11. https://doi.org/10.1080/00063658609476884

Ropert-Coudert, Y., Beaulieu, M., Hanuise, N., & Kato, A. (2009). Diving into the world of biologging. *Endangered Species Research*, *10*, 21–27. https://doi.org/10.3354/esr00188

Rossum, G. van, & Drake, F. L. (2010). *The Python language reference* (Release 3.0.1 [Repr.]). Python Software Foundation.

Rowcliffe, J., Carbone, C., Jansen, P. A., Kays, R., & Kranstauber, B. (2011). Quantifying the sensitivity of camera traps: An adapted distance sampling approach: *Quantifying camera trap sensitivity*. *Methods in Ecology and Evolution*, *2*(5), 464–476. https://doi.org/10.1111/j.2041-210X.2011.00094.x

Rowcliffe, J. M., & Carbone, C. (2008). Surveys using camera traps: Are we looking to a brighter future? *Animal Conservation*, *11*(3), 185–186. https://doi.org/10.1111/j.1469-1795.2008.00180.x

Rutz, C., & Troscianko, J. (2013). Programmable, miniature video-loggers for deployment on wild birds and other wildlife. *Methods in Ecology and Evolution*, *4*(2), 114–122. https://doi.org/10.1111/2041-210x.12003

Skalski, P. (2019). *Make Sense* [Computer software]. https://github.com/SkalskiP/make-sense/

Swan, M., Di Stefano, J., & Christie, F. (2014). Comparing the effectiveness of two types of camera trap for surveying ground-dwelling mammals. In *Camera trapping: Wildlife management and research* (pp. 123–130). CSIRO Publishing.

Tan, M., & Le, Q. V. (2021). *EfficientNetV2: Smaller Models and Faster Training* (arXiv:2104.00298). arXiv. http://arxiv.org/abs/2104.00298

TensorFlow Developers. (2023). *TensorFlow* (v2.12.1) [Computer software]. Zenodo. https://doi.org/10.5281/ZENODO.4724125

Urlus, J., McCutcheon, D., Gilmore, D., & McMahon, J. (2014). The effect of camera trap type on the probability of detecting different size classes of Australian mammals. In *Camera trapping: Wildlife management and research* (pp. 111–122). CSIRO Publishing.

Weinstein, B. G. (2015). M otion M eerkat: Integrating motion video detection and ecological monitoring. *Methods in Ecology and Evolution*, *6*(3), 357–362. https://doi.org/10.1111/2041-210X.12320

Welborne, D. (2014). Using camera traps to survey diurnal terrestrial reptiles: A proof of concept. In *Camera trapping: Wildlife management and research* (pp. 225–232). CSIRO Publishing.

Wilson, R. P., & McMahon, C. R. (2006). Measuring devices on wild animals: What constitutes acceptable practice? *Frontiers in Ecology and the Environment*, *4*(3), 147–154. https://doi.org/10.1890/1540-9295(2006)004[0147:MDOWAW]2.0.CO;2

Wüst, W. (1986). *Avifauna Bavariae—Die Vogelwelt Bayerns im Wandel der Zeit* (1st ed.). Gebrüder Geiselberger.

Young, S. (2016). *CCTV for wildlife monitoring: An introduction*. Pelagic Pub Ltd.

Manuscript 5 - No effects of paddle strokes on hatching rates of later developmental stages of river trout *Salmo trutta fario*

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Abstract

Paddling activities like kayaking are said to affect fish populations. We used systematic experiments (6 treatments x 5 repetitions) to study the effects of paddle strokes and sediments on spawn of river trout *Salmon trutta fario* and found no negative effect on hatching rate. The development of fungal growth differed non-systematically between treatments. It is possible that different mechanisms lead to the lower fungal growths of these treatments, which cancel each other out when combined, but the differences may also result from few strong infection outbreaks in single water tanks due to self-enforcing processes of fungal growths. The study began with spawn in the eye-stage (25 days old). While our findings thus show that the egg development from eye-stage to larvae (with depleted yolk sac) are unaffected by paddling activities, we cannot rule out possible effects on more sensitive earlier developmental stages. Experiments under more natural conditions may be able to address this problem. However, assessing the bottleneck in the fishes' live cycle causing negative population development is challenging due to the multitude of factors that influence fish reproduction in more natural habitats, including sediment influx from agricultural fields as well as interactions with fish stocking.

Introduction

Recreational activities in nature are important for the physical and mental well-being of humans (Stott 2019; BMU 2021; BMU 2023). Bodies of water especially attract many recreationists (Jennings 2007), with kayaking being one of the fastest growing activities in the US (Bell et al. 2007). Regionally, this may lead to conflicts of paddling activity with other interests like fishing and nature conservation. These conflicts are fanned by worries about negative effects on local fauna by e.g. scaring breeding or foraging birds and fish away (Zauner & Ratschan 2004), or direct mechanical inmacts on fish like injuries, destruction of spawn or increased sedimentation. However, there seldom is scientific evidence for these claims (Zauner & Ratschan 2004). Additionally, most mechanical impacts can be avoided by proper or experienced conduct and are not distinguishable from naturally occurring mechanical impacts, e.g. debris or deluge (Zauner & Ratschan 2004).

It is difficult to argue that an increase in recreational activity is the cause of decreasing reproduction rates in fish, since in the same period other factors affecting reproduction rates have changed drastically (Zauner & Ratschan 2004). One of them is the degradation of the gravel substrate due to an increase of agricultural activity. Fish like european grayling *Thymallus thymallus,* huchen or danube salmon *Hucho hucho*, brook lamprey *Lampetra planeri* and the model organism of this study river trout *Salmo trutta fario* need gravel substrate to spawn eggs. Suspended matter can lead to a degradation of gravel. Particularly fine sediments with a particle size of <0.85 mm to 1 mm are the main trigger for external colmation (covering gravel with fine sediment) and internal colmation (filling gaps between gravel with fine sediment) (Kondolf 2000, Soulsby et al. 2000, Sutherland et al. 2002, Schälchli et al. 2002). Forested areas supply extremely few suspended matter into bodies of water, whereas agricultural used areas suffer very high soil erosion, which can be displaced into bodies of water (Schwertmann et al 1990). In Bavaria, Germany, about 3 t soil per ha end up in bodies of water (Jung 1990, Auerswald 2006). Gravel substrate degenerated by colmation has a reduced usefulness as a spawning site because of restricted supply of oxygen and fresh water and restricted removal of metabolic products (Schälchli 2002, Niepagenkemper 2003 A & B).

Fish stocking, the wide-spread practice to counteract species decline (Armstrong & Seddon 2008, Lorenzen et al. 2012, Sass et al. 2017) not always enhance fish abundance (Radinger et al. 2023) and may influence recreational activity along with a multitude of effects on food webs (Eby et al. 2006) or by introducing non-native genotypes (Laikre et al. 2010).

In this study, we want to start assessing whether paddling activity negatively affects fish spawn. Paddle strokes may inhibit spawn development, lead to higher rates of fungal infestation, or even damage or kill spawn. Resolving that question would help obtaining important knowledge for regulating aquatic outdoor activities and resolve conflicts in recreational spaces.

Selected study species

For our study, we chose the river trout *Salmon trutta fario* as our model organism, since it is an indicator species in freshwater systems and has been used before for study purposes (Dvorak et al 2020). River trout are common all over Europe and are classified by the IUCN as least concern (IUCN 2012). They require fresh and clear water that is cool in the summer and rich in oxygen. For optimal egg development, sources differ lightly in the suggested oxygen level (Davis 1975, Kondolf 2000, Niepagenkemper et al 2003 A, Rubin et al 2004, Schreckenbach 2010, Turnpenny & Williams 1980) but all suggest high oxygen content of at least 2-10 mg/l.

River trout spawn from October until January in water depths of 10 – 50 cm (Jungwirth 2003). The fertilized eggs develop until spring, which takes 1.5 to 5 months, depending on temperature (Elliott et al 1994, Geldhauser & Gerstner 2003). River trout are brood hiders, meaning they slap a spawning pit into a gravel substrate, perform their mating ritual above the pit so that the fertilized eggs sink into the pit, and burry their spawn under a blanket of gravel (Barlaup et al 1994, Grost et al 1991, Jungwirth 2003). For this, river trout need loose gravel substrate and a lotic water, meaning flowing waters. The spawn is photosensitive and begins to be sensitive to being moved already one day after fertilization, which remains so until the eyes are formed (Pulg 2009). River trout are one of the most affected species by gravel substrate degradation since the stability and permeability of the substrate influence the biggest factor of spawn survival, which is oxygen supply (Walker & Bayliss 2007, Pulg 2009). For optimal egg development, sources specify different temperatures, ranging between 0°Celsius and 13° Celsius (0°-13° (Elliott 1981); 5° (Humpesch 1985); 7° (Jungwirth & Winkler 1984)). Newly hatched river trout larvae have a yolk sack from which they feed themselves. The larvae are mobile but keep to the gravel. After 3 to 6 weeks, the larvae deplete their yolk sack and emerge to the surface to fill their swim bladder (Elliott 1994, Jungwirth 2003). They are now fully developed fish.

Methods

In this study, we experimentally evaluated the impact of sediment and paddle strokes on fish spawn, resulting in six treatment groups, each containing five tanks as repetitions (figure 1).

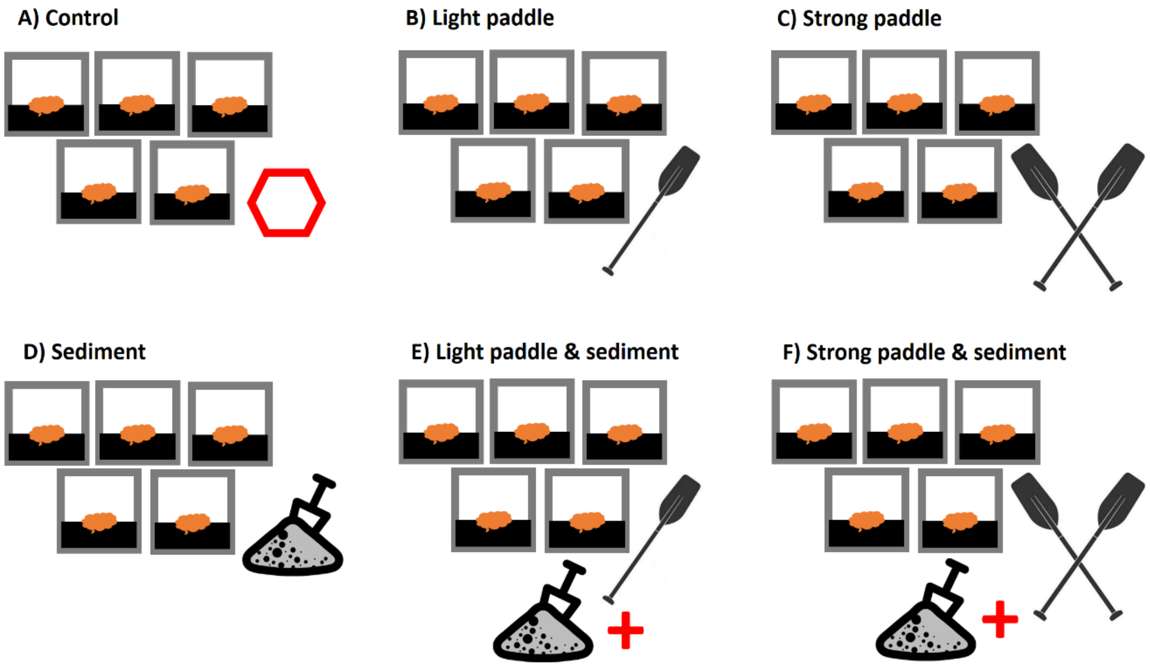

Figure 1. Visualization of the 6 treatment groups (A-F). Each group consisted of 5 tanks, outfitted with substrate, filters, water, and approximately 1.000 fertilized eggs of river trout.

The tanks measured 30cm x 20 cm on the base and 20 cm in height. They were filed to 1/4 with black gravel substrate with an average particle size of 2-4 cm. Water level was about 5 cm below the edge. Each tank was outfitted with a mini internal filter (Eheim Skim 350, Eheim, Germany). The study was conducted in a cooling chamber and the tanks were covered with plastic covers to keep air moisture low.

Every tank contained about 1000 fertilized eggs of river trout *Salmo trutta fario*. Eggs of river trout are very sensitive to light and vibration between fertilisation and eye-stage (LANUV 2022). This is why we conducted our study with eggs aged 25 days and already in the eye-stage. Most European fish species spawn in winter or spring, e.g. european grayling *Thymallus thymallus,* huchen or danube salmon *Hucho hucho* and european bullhead *Cottus gobio* all spawn from March to April (Freyhof 2011, Freyhof & Kottelat 2008, LAVES 2011). Scince winter and spring are very unattractive seasons for paddling activity, with most recreational paddling being carried out in summer, we feel it is justified not experimenting with the most fragile developmental stage.

The same person applied treatments every day for the duration of the study. Treatment 1 (T1) received three light paddle strokes, moving only the water column, while treatment 2 (T2) received three strong paddle strokes, moving the water column and the tanks substrate. Treatment 5 (T5) received a solution of 10g fine dried sediment and water. Treatment 3 (T3) first received the same solution as T5, followed by three light paddle strokes. Treatment 4 (T4) also received the sediment solution, followed by three strong paddle strokes. Treatment 6 (T6) was the control group for this study and received no treatment.

For maintaining and data collection, the daily routine was as follows: Every two days the same two people carefully exchanged the water in all tanks. They removed the plastic covers, switched of the filters for the group that was being worked on and exchanged the water slowly, taking great care not to disturb the spawn or substrate. Since our model organisms' requirements for water quality agreed with the local tap water, we chilled tap water in containers over night as to achieve the required temperature. After the water exchange, the person applying the treatments proceeded, took note of the room temperature and visually evaluated water quality and tank filters. Next, they turned off the filters group by group to collect and count dead eggs and larvae or eggs presenting fungal growths due to infestation. After that, they turned the filters back on. After evaluation, treatments were applied and plastic covers were put back on. Since at day 10 of the study, the number of hatched larvae became too great to count, the person applying treatments estimated this number. On day 16, the last day of the study, we counted the exact number of larvae. With this, we reviewed the initial estimate and calculated the deviation. This resulted in two sets of data tables: original data (OD, with in-field estimates) and corrected data (CD, with model-generated numbers instead of in-field estimates).

During experimentation, this study was confronted with unexpected events. Nevertheless, we are confident in our data and results. On day 14 of the experiment, the power to the coolingroom was cut. We were able to power the filters in the tanks and lights to conduct our daily tasks. Power was restored early the next day, which is when the room started to cool down again. Overall, the tanks had been approximately 4h without filters and about 1 full day in elevated temperatures. Additionally, on day 15 of the experiment, after applying the treatments to the sediment group and the control group, we overlooked to turn the filters back on. Both groups were without filters over night, leading to nearly all larvae dying. We compensated for the loss of data with modelling the entry for day 16 (end of experiment) for these treatments, based on their development beforehand. For this, we used the same method as for OD and CD.

Results

Number of hatched larvae

In our experiment, the number of larvae developed similarly in all treatment groups (figure 2). On day 9 most larvae hatched in all treatments, with number of living larvae slowly declining over the course of the sturdy. On day 11, an ANOVA analysis of the estimated number of alive larvae shows a difference between groups (Df=24, F=2.742, p=0.043). Using Tukey's method, we found a slight difference (p=0.036) only between sediment treatment (mean=350.0, sd=35.4) and combined sediment & strong paddle treatment (mean=240.0, sd=22.4). On day 16, an ANOVA analysis of the estimated number of alive larvae shows no difference between groups.

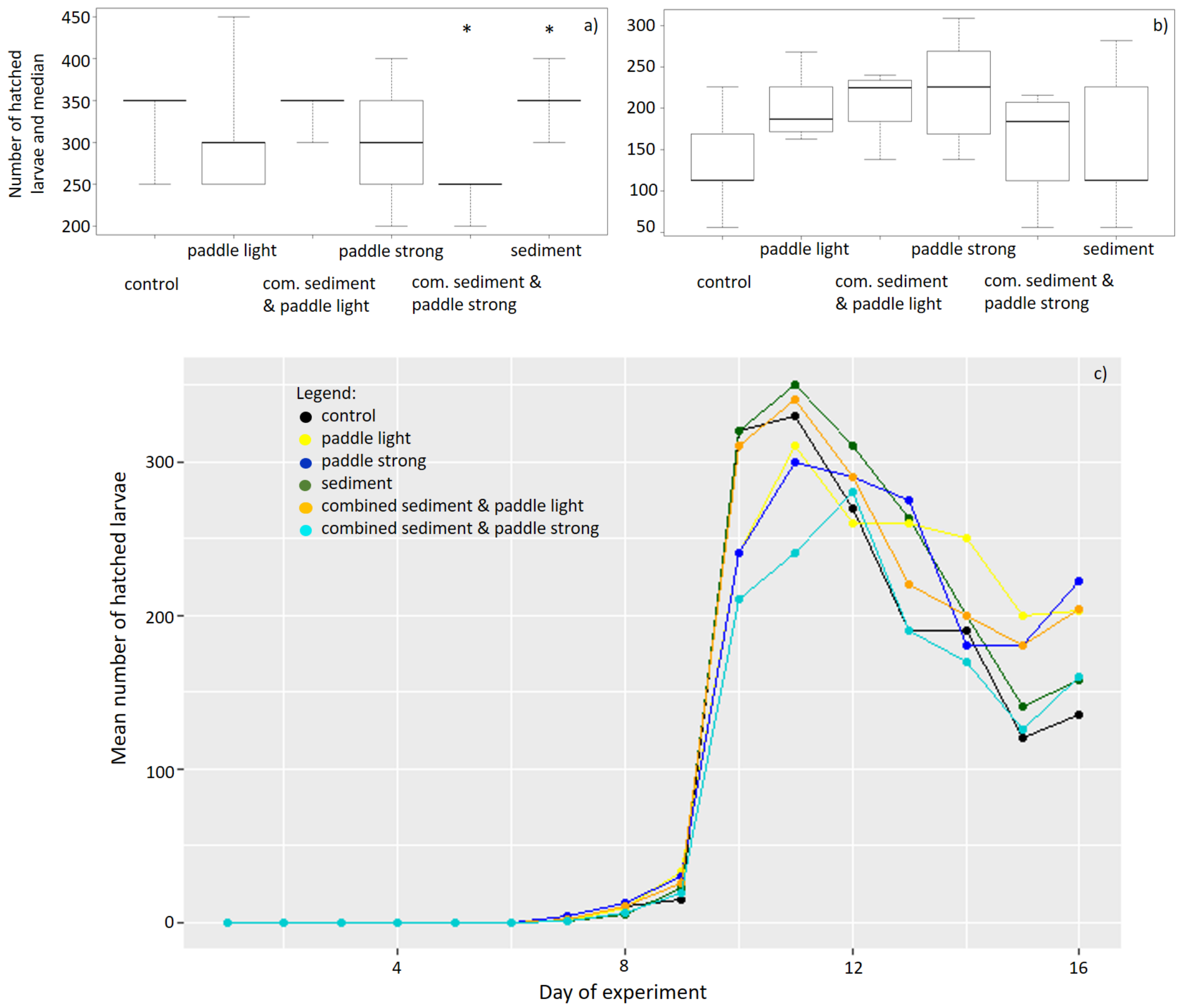

Figure 2. Overview of the development of the number of hatched larvae for all treatments. A) Boxplot of the numbers of larvae compared between all treatment groups on day 11. Each treatment group contains five tanks with ~1000 eggs each. B) Boxplot of the numbers of larvae compared between all treatment groups on day 16. Each treatment group contains five tanks with ~1000 eggs each. C) Mean number of hatched larvae over the course of the study for every treatment group. Each treatment group contains five tanks with ~1000 eggs each. Black = control, blue = sediment, yellow = light paddle, orange = strong paddle, pink = light paddle & sediments, purple = strong paddle & sediments

Development of fungal growths

In contrast to the number of hatched larvae, we found differences in the development of fungal growths in our experiments between treatments (figure 3). These growths happen due to naturally occurring funguses and can lead to infestation of eggs or larvae. They present as a white, irregular growth, leading to the hosts' death. On day 11, an ANOVA analysis of the estimated number of alive larvae shows a difference between groups (Df=24, F= 3.533, p=0.016). Using Tukey's method, we found a difference (p=0.012) between sediment treatment (mean=162.6, sd=34.8) and control treatment (mean=229.0, sd=23.4) and a difference (p=0.023) between sediment treatment (mean=162.6, sd=34.8) and combined sediment & light paddle treatment (mean=224.0, sd=13.4). On day 15, an ANOVA analysis of the development of fungal growths shows a difference between groups (Df=24, F= 4.272, p=0.006). Using Tukey's method, we found a difference (p= 0.013) between light paddle treatment (mean=337.4, sd=60.4) and combined sediment & strong paddle treatment (mean=497.2, sd=80.1) and a difference (p=0.035) between sediments treatment (mean=356.8, sd=96.7) and combined sediment & strong paddle treatment (mean=497.2, sd=80.1).

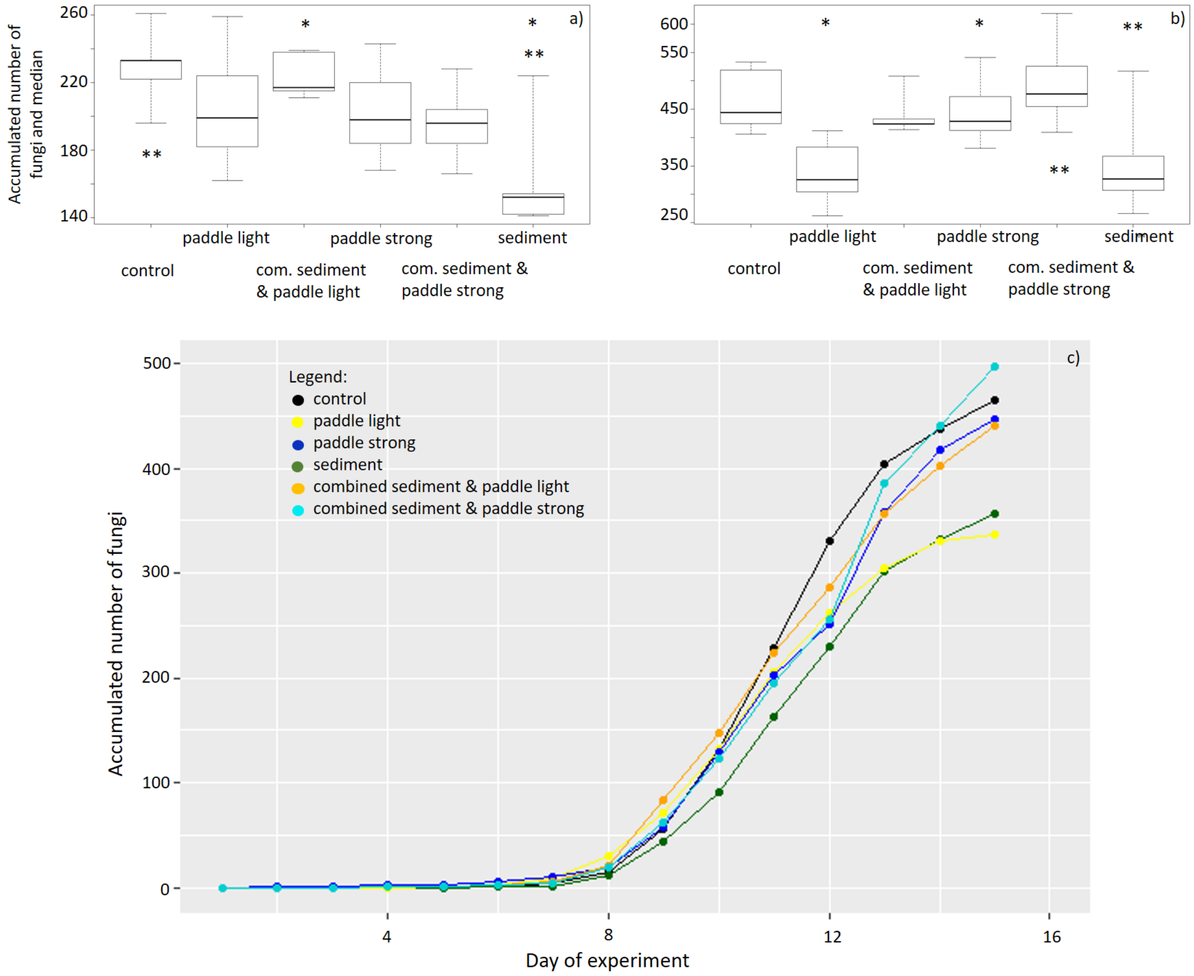

Figure 3. Overview of the developments of fungal growths, presenting itself as an irregular white growth on infected eggs or larvae. A) Boxplot of fungal growth compared between all treatment groups on day 11. Each treatment group contains five tanks with ~1000 eggs each. B) Boxplot of fungal growth compared between all treatment groups on day 15. Each treatment group contains five tanks with ~1000 eggs each. C) Development of fungal growths over the course of the study for every treatment group. Each treatment group contains five tanks with ~1000 eggs each. Black = control, blue = sediment, yellow = light paddle, orange = strong paddle, pink = light paddle & sediments, purple = strong paddle & sediments

Discussion

In this study, we explored the impact of paddling activity and sediment on hatching rate of river trout *Salmo trutta fario* spawn and development of fungal growths. We did not find a difference between treatments concerning the number of hatched larvae. Sediment, light and strong paddle strokes and combined treatments all lead to similar hatching rates to the control treatment. We could thus not find any indications that paddle activity is the trigger of decreased hatching rates or spawn die-off for the in our study investigated eggs that have reached the eye-development stage. Concerning the development of fungal growths, we found minor effects. These did not perpetuate systematically, e.g. the lower fungal growth rate observed in sediments treatment and light paddle treatment did not appear in the respective combined treatment. It is possible that different mechanisms lead to the lower fungal growths of these treatments, which cancel each other out when combined. It is also possible that self-enforcing processes of fungal growth in single water tanks may have caused the observation.

In our study, we worked with spawn already in the eye stage - meaning we did not experiment with the most fragile developmental stage, which is difficult to handle and to maintain. Still, we are confident in the relevance of our result, since most European fish species spawn in winter or spring, e.g. european grayling *Thymallus thymallus,* huchen or danube salmon *Hucho hucho* and european bullhead *Cottus gobio* all spawn from March to April (Freyhof 2011, Freyhof & Kottelat 2008, LAVES 2011). These seasons are unattractive for paddling activity and especially recreational paddling activities are performed mostly in summer.

Our experimental setup could not identify any hint for paddling activity or sedimentation to be the direct cause for declining fish reproduction. In more natural systems, assessing the bottleneck in the fishes' live cycle causing negative population development is challenging due to the multitude of factors that influence fish reproduction, including sediment influx from agricultural fields as well as interactions with fish stocking. The absence of eggs may result from missing adult fish or strong predation. If larvae are missing, then the substrate might be compromised. If breeding areas or areas with juveniles are missing, there might be high predation (von Siemens et al. 2012), which may result from faulty fish stocking. In addition, several human-induced factors can cause low fish stock or missing life stages, e.g. settlements, forestry, waterway construction and maintenance, industry, agriculture, urbanization, (river) navigation, traffic and power generation (von Siemens et al. 2012). These factors can reduce fish stock on different levels. The level of mortality can be increased through structural deficits, poisoning or deadly injuries by e.g. turbines. Reproduction levels are reduced by a shortage of spawning grounds and habitats for juvenile fish reduce reproduction, but also by a lack of adult fish. On the genetic level, natural genetic exchange and repopulation are hampered by loss of connections between bodies of water and habitat fragmentation (von Siemens et al. 2012), e.g. by traversing structures.

Since we cannot discern a single factor to remove or manage to improve fish stock, an ecosystem-based assessment and management of affected areas would be best (O´Higgins et al. 2020). It is a costly approach, which often calls regional practices into question (Ruckelshaus et al. 2008) and can fail when not applied wide-ranging enough or without addressing the key bottleneck (Palmer & Ruhi 2019). For the European grayling Thymallus

thymallus, an ecosystem-based assessment was attempted (Mattes & Meyer 2001) but failed due to too few eggs at spawning sites. Still, focusing on re-establishing ecological processes and habitats will have a stronger long-term effect than actions against single factors (Radinger et al 2023).

Statements and Declarations

Competing interests: The authors have no relevant financial or non-financial interests to disclose.

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Data availability: The datasets generated during and/or analysed during the current study are available in the PaddleStrokeAndFishSpawn repository, https://github.com/AMSchweizer/PaddleStrokeAndFishSpawn

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References

Armstrong, D., & Seddon, P. (2008). Directions in reintroduction biology. *Trends in Ecology & Evolution*, *23*(1), 20–25. https://doi.org/10.1016/j.tree.2007.10.003

Auerswald, K. (2006). Germany. In J. Boardman & J. Poesen (Eds.), *Soil Erosion in Europe* (pp. 213–230). John Wiley & Sons, Ltd. https://doi.org/10.1002/0470859202.ch18

Barlaup, B. T., Lura, H., Sægrov, H., & Sundt, R. C. (1994). Inter- and intra-specific variability in female salmonid spawning behaviour. *Canadian Journal of Zoology*, *72*(4), 636–642. https://doi.org/10.1139/z94-086

Bell, S., Tyrväinen, L., Sievänen, T., Pröbstl, U., & Simpson, M. (2007). Outdoor Recreation and Nature Tourism: A European Perspective. *Living Reviews in Landscape Research*, *1*. https://doi.org/10.12942/lrlr-2007-2

BMUV. (2023, January 30). *Politik des BMUV für Nachhaltigkeit im Sport*. https://www.bmuv.de/themen/nachhaltigkeit-digitalisierung/tourismus/politik-des-bmuv-fuer-nachhaltigkeit-im-sport

BMUV Members of the Advisory Board. (2021). *SUSTAINABLE SPORT 2030 – Responsibility for Nature, the Environment and Society*. BMUV Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Tourismus_Sport/positionspapier_nachhaltiger_sport_2030_2112_en_bf.pdf

Davis, J. C. (1975). Minimal Dissolved Oxygen Requirements of Aquatic Life with Emphasis on Canadian Species: A Review. *Journal of the Fisheries Research Board of Canada*, *32*(12), 2295–2332. https://doi.org/10.1139/f75-268

Dvorak, P., Roy, K., Andreji, J., Liskova, Z. D., & Mraz, J. (2020). Vulnerability assessment of wild fish population to heavy metals in military training area: Synthesis of a framework with example from Czech Republic. *Ecological Indicators*, *110*, 105920. https://doi.org/10.1016/j.ecolind.2019.105920

Eby, L., Roach, W., Crowder, L., & Stanford, J. (2006). Effects of stocking-up freshwater food webs. *Trends in Ecology & Evolution*, *21*(10), 576–584. https://doi.org/10.1016/j.tree.2006.06.016

Elliott, J. M. (1981). Some aspects of thermal stress on freshwater teleosts. *Stress and Fish*, 209–245.

Freyhof, J. (2011). *Thymallus thymallus. The IUCN Red List of Threatened Species*. IUCN Red List. https://www.iucnredlist.org/species/21875/9333742

Freyhof, J., & Kottelat, M. (2008). *Hucho hucho. The IUCN Red List of Threatened Species*. https://www.iucnredlist.org/species/10264/3186143

Geldhauser, F., & Gerstner, P. (2022). *Der Teichwirt: Karpfen und Nebenfische* (10., aktualisierte Auflage). Ulmer.

Grost, R. T., Hubert, W. A., & Wesche, T. A. (1991). Description of Brown Trout Redds in a Mountain Stream. *Transactions of the American Fisheries Society*, *120*(5), 582–588. https://doi.org/10.1577/1548-8659(1991)120<0582:DOBTRI>2.3.CO;2

Humpesch, U. H. (n.d.). Inter specific and intra specific variation in hatching success and embryonic development of 5 species of salmonids and Thymallus thymallus. *Archiv für Hydrobiologie*, *104*(1), 129–144.

Ingendahl, D. (1999). *Der Reproduktionserfolg von Meerforelle (Salmo trutta L.) und Lachs (Salmo salar L.) in Korrelation zu den Milieubedingungen des hyporheischen Interstitials* [Dissertation, Univertität Kölln]. https://nwbib.de/BT000176564

IUCN. (2010). *Salmo trutta: Freyhof, J.: The IUCN Red List of Threatened Species 2013: e.T19861A9050312* [dataset]. International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.UK.2008.RLTS.T19861A9050312.en

Jennings, G. (Ed.). (2007). *Water-based tourism, sport, leisure, and recreation experiences*. Elsevier.

Jung, W.-D. (1990). *Berechnung der Bodenerosion im Moosach-Amper-Hügelland bei Freising mit Hilfe eines digitalen Geländemodells* [Diplomarbeit]. Technische Universität München.

Jungwirth, M. (Ed.). (2003). *Angewandte Fischökologie an Fließgewässern*. Facultas.

Jungwirth, M., & Winkler, H. (1984). The temperature dependence of embryonic development of grayling (Thymallus thymallus), Danube salmon (Hucho hucho), Arctic char (Salvelinus alpinus) and brown trout (Salmo trutta fario). *Aquaculture*, *38*(4), 315–327. https://doi.org/10.1016/0044-8486(84)90336-3

Kondolf, G. M. (2000). Assessing Salmonid Spawning Gravel Quality. *Transactions of the American Fisheries Society*, *129*(1), 262–281. https://doi.org/10.1577/1548-8659(2000)129<0262:ASSGQ>2.0.CO;2

Laikre, L., Schwartz, M. K., Waples, R. S., & Ryman, N. (2010). Compromising genetic diversity in the wild: Unmonitored large-scale release of plants and animals. *Trends in Ecology & Evolution*, *25*(9), 520–529. https://doi.org/10.1016/j.tree.2010.06.013

LANUV - Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen. (2022). *Die Vermehrung von Salmoniden*. https://www.lanuv.nrw.de/fileadmin/lanuv/natur/aquakultur/2022/Vermehrung_von_Salmoniden_Web.pdf

LAVES Niedersächsisches Landesamt für Verbraucherschutz und Lebensmittelsicherheit, Dez. Binnenfischerei. (2011). *Vollzugshinweise zum Schutz von Fischarten in Niedersachsen. – Fischarten des Anhangs II der FFH-Richtlinie und weitere Fischarten mit Priorität für Erhaltungs- und Entwicklungsmaßnahmen – Koppe, Groppe oder*

Mühlkoppe (Cottus gobio). – Niedersächsische Strategie zum Arten und Biotopschutz. LAVES Niedersächsisches Landesamt für Verbraucherschutz und Lebensmittelsicherheit. file:///C:/Users/bt306529/Downloads/E14_VZH_Koppe_Nov-2011.pdf

Lorenzen, K., Beveridge, M. C. M., & Mangel, M. (2012). Cultured fish: Integrative biology and management of domestication and interactions with wild fish. *Biological Reviews*, *87*(3), 639–660. https://doi.org/10.1111/j.1469-185X.2011.00215.x

Mattes, H., & Meyer, E. I. (2001). *Kanusport und Naturschutz – Forschungsbericht über die Auswirkungen des Kanusports an Fließgewässern in NRW*. https://docplayer.org/73796186-Kanusport-und-naturschutz-forschungsbericht-ueber-die-auswirkungen-des-kanusports-an-fliessgewaessern-in-nrw.html

Niepagenkemper, O., & Meyer, E. I. (2003). *Messungen der Sauerstoffkonzentration in Flusssedimenten zur Beurteilung von potentiellen Laichplätzen von Lachs und Meerforelle*. Landesfischereiverband Westfalen-Lippe.

Niepagenkemper, O., Schulte, U., & Mayer, E. I. (2003). *Pilotmaßnahmen zur Verbesserung des Sauerstoffgehalts in potenziellen Laichgebieten des Atlantischen Lachses im Siegsystem*. Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz des Landes Nordrhein-Westfalen.

O'Higgins, T. G., Lago, M., & DeWitt, T. H. (Eds.). (2020). *Ecosystem-Based Management, Ecosystem Services and Aquatic Biodiversity: Theory, Tools and Applications*. Springer International Publishing. https://doi.org/10.1007/978-3-030-45843-0

Palmer, M., & Ruhi, A. (2019). Linkages between flow regime, biota, and ecosystem processes: Implications for river restoration. *Science*, *365*(6459), eaaw2087. https://doi.org/10.1126/science.aaw2087

Parkin, G. W., Gardner, W. H., & Auerswald, K. (2008). Water Erosion. In W. Chesworth (Ed.), *Encyclopedia of Soil Science* (pp. 817–822). Springer Netherlands. https://doi.org/10.1007/978-1-4020-3995-9_625

Pulg, U. (2009). *Laichplätze der Bachforelle (Salmo trutta) in der Moosach – die Bewertung ihrer Funktionsfähigkeit, ihre Degradierung und ihre Restaurierung*. Technische Universität München.

Radinger, J., Matern, S., Klefoth, T., Wolter, C., Feldhege, F., Monk, C. T., & Arlinghaus, R. (2023). Ecosystem-based management outperforms species-focused stocking for enhancing fish populations. *Science*, *379*(6635), 946–951. https://doi.org/10.1126/science.adf0895

Rubin, J.-F., Glimsater, C., & Jarvi, T. (2004). Characteristics and rehabilitation of the spawning habitats of the sea trout, Salmo trutta, in Gotland (Sweden). *Fisheries Management and Ecology*, *11*(1), 15–22. https://doi.org/10.1111/j.1365-2400.2004.00349.x

Ruckelshaus, M., Klinger, T., Knowlton, N., & DeMaster, D. P. (2008). Marine Ecosystem-based Management in Practice: Scientific and Governance Challenges. *BioScience*, *58*(1), 53–63. https://doi.org/10.1641/B580110

Sass, G. G., Rypel, A. L., & Stafford, J. D. (2017). Inland Fisheries Habitat Management: Lessons Learned from Wildlife Ecology and a Proposal for Change. *Fisheries*, *42*(4), 197–209. https://doi.org/10.1080/03632415.2017.1276344

Schälchli, Abeg, & Hunzinger. (2002). *Kolmation. Methoden zur Erkennung und Bewertung. Schlussbericht* (p. 26). Eidg. Anstalt für Wasserversorgung, Abwasserreinigung und Gewässerschutz EAWAG. https://www.dora.lib4ri.ch/eawag/islandora/object/eawag%3A14832

Schreckenbach, K. (2010). *Gesungheit und hygiene—Basis für Wachstum*.

Schwertmann, U., Vogl, W., & Kainz, M. (1990). *Bodenerosion durch Wasser Vorhersage des Abtrags und Bewertung von Gegenmassnahmen* (2. Aufl). Ulmer.

Soulsby, C., Youngson, A. F., Moir, H. J., & Malcolm, I. A. (2001). Fine sediment influence on salmonid spawning habitat in a lowland agricultural stream: A preliminary assessment. *Science of The Total Environment*, *265*(1–3), 295–307. https://doi.org/10.1016/S0048-9697(00)00672-0

Stott, T. (2019). Water Sports and Water-Based Recreation. In D. Huddart & T. Stott, *Outdoor Recreation* (pp. 331–359). Springer International Publishing. https://doi.org/10.1007/978-3-319-97758-4_13

Sutherland, A. B., Meyer, J. L., & Gardiner, E. P. (2002). Effects of land cover on sediment regime and fish assemblage structure in four southern Appalachian streams: *Land cover effects on sedimentation and fish*. *Freshwater Biology*, *47*(9), 1791–1805. https://doi.org/10.1046/j.1365-2427.2002.00927.x

Turnpenny, A. W. H., & Williams, R. (1980). Effects of sedimentation on the gravels of an industrial river system. *Journal of Fish Biology*, *17*(6), 681–693. https://doi.org/10.1111/j.1095-8649.1980.tb02802.x

von Siemens, M., Hanfland, S., & Braun, M. (2012). *Fischbesatz in angelfischereilich genutzten Gewässern*. Landesfischereiverband Bayern e.V.

Walker, A. M., & Bayliss, B. D. (2007). The Spawning Habitat Requirements of Sea Trout: A Multi-Scale Approach. In G. Harris & N. Milner (Eds.), *Sea Trout: Biology, Conservation and Management* (pp. 325–341). Blackwell Publishing Ltd. https://doi.org/10.1002/9780470996027.ch21

Zauner, G., & Ratschan, C. (2004). *Auswirkungen des Kanusports auf die Fischfauna*. Studie im Auftrag des Deutschen Kanuverbandes e. V. file:///C:/Users/bt306529/Downloads/1489943154-Studie-zu-den-Auswirkungen-des-Kanusports-auf-die-Fischfauna.pdf

List of manuscripts by Anne-Maria Schweizer

Schweizer A.-M., Leiderer A., Mitterwallner V., Walentowitz A., Mathes G. H., & Steinbauer M. J. (2021). Outdoor cycling activity affected by COVID-19 related epidemic-control-decisions. *PLOS ONE*, *16*(5), e0249268. https://doi.org/10.1371/journal.pone.0249268

Schweizer A.-M., Höschler L., & Steinbauer M. J. (2021). The Physical Damage of Climbing Activity on Sandstone Lichen Cover. *Sustainability*, *13*(24), 13590. https://doi.org/10.3390/su132413590

Magioli M., Carvalho E. A. R., Sampai R., Püttker, T., Arlt S., Hanoeman W., Mattai R., Ooms A., Schweizer A.-M., Scriba M., Köhl M., & Ganzhorn J. U. (2023). Mammal diversity and composition are not affected by certified timber extraction in Suriname. *Forest Ecology and Management*, *541*, 121080. https://doi.org/10.1016/j.foreco.2023.121080

Schweizer A.-M., Schulte C., Steinbauer M.J. The influence of recreational activities on temporal feeding patterns of the common kingfisher (*Alcedo atthis*). Submitted to Animal Conservation (manuscript ID ACV-10-24-OMR-265).

Schweizer A.-M., Schweizer J., Steinbauer M.J. Overcoming the challenge of remotely monitoring small birds using video traps and artificial intelligence: An example with the common kingfisher *Alcedo atthis*. Submitted to AI & Society (manuscript ID f7d153dd-dadd-4f7b-b366-ae4b1a997353).

Schweizer A.-M., Schuster S., Steinbauer M.J. Effects of paddle strokes on hatching rates of river trout *Salmo trutta fario*. Submitted to Fisheries Oceanography (manuscript ID FOG-24-2061).

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