Has tourism impacted the 'gentoofication' of the Antarctic peninsula over the past two decades?

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Abstract

The seaborne tourism industry in the Western Antarctic Peninsula (WAP) has been growing rapidly in the past two decades. Simultaneously, the WAP has been experiencing a ‘gentoofication’ where gentoo penguin populations have been expanding rapidly. Subsequently, there have been growing concerns for impacts of tourism on population dynamics as the number of tourist landings at penguin colonies increase. The goal of this study was to examine how or if increases in tourism activities impact gentoo penguin populations dynamics in the region. Of 28 selected colonies, 17 show positive linear trends in the number of counted nests suggesting population growth, and 11 colonies show negative linear trends in the number of counted nests suggesting decline. Gentoo penguin population growth trends at visited sites were 57% lower than those at non-visited sites, yet the mechanism for this has yet to be identified. A predictive analysis found that the model could only account for 32.51% of the variability in nest counts with the most important variables being season and location (in degrees latitude), followed by the standardised median number of passengers, total number of passengers and number of landings. Finally, a time-lag analysis suggested that tourism parameters from both three- and five-years prior were a not a significant predictor of nest counts in the current year. Despite these results, continued monitoring of these relationships will be critical to managing Antarctic penguin populations during the current era characterised by increasing tourist traffic and pressures from climate change.

Introduction

Antarctic tourism has expanded rapidly in the past two decades and represents an industry with stakeholders in many parts of the world (Bender et al. 2016, ATCM 2023, Bastmeijer 2023, Makanse 2024). Most tourism is focused on the western Antarctic peninsula (WAP), due to its relative accessibility compared to the rest of the continent. Most passengers travel to Argentina or Chile by aircraft, then board ships heading south. The size of the vessels varies from small yachts (carrying 12 or fewer passengers) to vessels carrying more than 500 passengers which are not permitted to make landings in Antarctica. The most common vessels heading to Antarctica with passengers are the expedition ships, carrying between 13 and 200 visitors who travel to experience the land and seascapes and view the unique ecosystem.

Under the Antarctic Treaty System, tourism is managed through the Antarctic Treaty Consultative Meeting (ATCM) with the Protocol on Environmental Protection, adopted in 1991, providing a regulatory framework for almost all human activity in Antarctica. Currently, most Antarctic tour operators are members of the International Association of Antarctica Tour Operators (IAATO) which requires its members to adhere to legally binding ATCM Measures. In terms of visitor management, current regulations include ATCM Measure 15 (2009) which allows a maximum of 100 visitors ashore at any time and requires that tour vessels coordinate with each other to ensure no more than one ship is at a landing site at any one time. A minimum actively guiding staff to passenger ratio of 1:20 must also be maintained. Additionally, the ATCM creates Visitor Site Guidelines for the most visited sites and IAATO member Operators are also required to follow site guidelines created by IAATO which follow a similar format to the ATCM (see https://www.ats.aq/devAS/Ats/VisitorSiteGuidelines?lang=e**).** Both ATCM and IAATO visitor site guidelines set additional requirements for responsible visitation for each site, including daily and seasonal limits on the number and size of ships that can visit, number of people ashore, activities and other restrictions, including closed areas. Further guidance from ATCM includes a minimum of 5m distance from all wildlife on land (ATCM, 2021).

Although not the most abundant species in Antarctica, the gentoo penguin (*Pygoscelis papua*), is the one most visited by tour operators. This has to do with colony accessibility (i.e., many gentoo penguin colonies are found in the sheltered area of the Gerlache Strait), where wind, swell, and ice conditions are the least likely to impact possible operations.

Gentoo penguins are the least common of the Pygoscelid (brush-tailed) species of penguin with an estimated global population of 387,000 breeding pairs (Lynch, 2013). They breed primarily in the region of the Scotia Arc (Falkland Islands (Malvinas), South Sandwich, South Orkney and South Shetland Islands, as well as the Western Antarctic Peninsula), where 80% of their population resides (IUCN, 2018). On the Western Antarctic Peninsula and the South Shetland Islands (including Elephant Island; hereafter the WAP region), there are an estimated 119,631 breeding pairs (Naveen and Humphries, 2022), distributed amongst 139 sites. Currently they are listed as “Least Concern” by the IUCN after a recent re-evaluation of their population trends (IUCN, 2016).

In the WAP region, monitoring projects tracking gentoo penguins have demonstrated that populations are generally increasing throughout the area. Most sites are showing increasing or stable populations, while a few exceptions are showing decreasing populations. Overall, the entire population of gentoos in the WAP region seems to be increasing, and the population expanding southward (Baylis et al. 2013, Clucas et al. 2014, Dunn et al. 2016, Lynch 2013, Naveen and Humphries 2022).

Despite the overall growing population of gentoo penguins and the measures in place to safeguard Antarctica from recreational human activity, there is still interest in determining if the growing tourism industry and associated colony visits are having a negative impact on population trends. To that effect, in recent years there have been several studies that have looked at this through various lenses.

Recently, a study by Dunn et al (2018) found a statistical link suggesting that higher numbers of passengers landing at Goudier Island (Port Lockroy) may be negatively affecting the numbers of nesting gentoo penguins, bearing in mind that this site has a research station with a resident team of researchers through the summer months, and has a very small overall surface area. They also report significant relationships with factors related to climate change. This is a change from work 20 years earlier which showed negligible impact from tourist visitation (Cobley and Shears 1999). However, the Cobley and Shears (1999) study was carried out only a few years after tourism began at Goudier Island (although data here have been collected since the colony was populated by gentoo penguins in 1985) and it is unlikely enough data were gathered to make any sort of conclusion. Follow up work by Trathan et al. (2008) demonstrated that nest counts at Goudier Island had been decreasing over time. The relationship with the number of visitations was tenuous in the Trathan et al. (2008) study, and it was suggested that observer disturbance (i.e., the resident research/conservation team) at Goudier Island might be leading to some of the patterns found. Another study at Petermann Island, south of the Lemaire Channel, found that breeding success of gentoo penguins was lower at visited colonies than non-visited ones, despite the increase in the number of nests over time (Lynch et al. 2010). Even though some negative trends between tourism and penguin breeding success have been uncovered, recent work has demonstrated that stress hormones as measured from guano samples were not significantly different between visited and not visited colonies (Lynch et al. 2019).

The most comprehensive study of tourism activity on the WAP to date is work from Stony Brook University (Bender et al. 2016). This work describes trends and patterns in tourism and identified areas that are showing increased vessel traffic and site visitation. The region between Brabant and Anvers Islands is the most heavily visited by expedition vessels, and monitoring of penguin colonies in this region is vital to understanding any possible impacts from Antarctic visitors.

The broad goals of this analysis were to a) report on current gentoo population trends at several key colonies around the WAP region, b) assess the relationship between several parameters derived from tourism data and gentoo penguin population trends, and c) use predictive analytics to determine if tourism data could be used to predict penguin populations.

Methods

Selected gentoo colonies

All gentoo penguin nest counts were downloaded from version 4.1 of the Mapping Application for Penguin Populations and Projected Dynamics (MAPPPD) website (www.penguinmap.com) which contains historical penguin census records up to the 2021/2022 breeding season. We use nest counts as they are more representative of the available breeding population than either chick or adult counts. To get a sampling of colonies that are spread throughout the WAP region, we selected 29 sites that had gentoo penguin nest count time series with more than 12 years of census records since 2003 (Humphries et al. 2017). Of those 29 sites, 8 were not visited by tourists, while 21 were those that have been visited at least once. Two of the 21 sites that were visited (Skottsberg Point and Selvick Cove) have only been visited extremely rarely with < 4 landings each since 2003.

Dependent variables

All landing data including the number of visiting passengers, the types of activities, dates, and total visit times were obtained from IAATO per a specific data request. Those data were provided in Text delimited format (.csv) and processed using the R Programming language.

Data were filtered to exclude activities where passengers did not land ashore including kayaking, ship cruising, zodiac cruising, remote underwater vehicle activities, anchoring, and helicopter flights. Because a season extends from late October in one year to March in the next year, we structured the data so visits in January through March were listed as occurring in the "season" delineated by the previous year. For example, visits in January - March 2012 were listed as occurring in the 2011 season. The data were further filtered to remove visits that occur after January because from late January through March, gentoos are off their nests and chicks are beginning to creche making it impossible to get nest counts. It is during the November – January period that we might expect passengers to have any direct impact on the number of breeding pairs. We did not include October in the analysis as the season usually starts very late in the month and we would not expect the limited number of visits to impact breeding success.

Data for each site were summarized as per Table 1.

Table 1
Variables derived from tourism (landing) data provided by IAATO

Variable	**Description**
Median number of passengers per season	The median number of passengers that landed at a site across all landing events between November and January
Maximum number of passengers landed	The maximum number of passengers that landed at a site at any point between November and January
Mean absolute deviation of passengers landing per season	This is a measure of the variation in the number of passengers landing
Minimum number of passengers landed	The minimum number of passengers that landed at a site at any point between November and January
Total number of visits	The sum total of all landings at a site per season from November to January
Median, maximum, and mean absolute deviation of number of passengers per month	Median, maximum and mean number of passengers landing at a site per month for the months of November to January
Median visit time	The median time (in seconds) ashore for all visits per season
Median effort	The median visit time divided by the median number of passengers to give a measure of effort at each colony (the amount of time ashore per passenger).
Total number of passengers	The sum total of all passengers landing at a site from November to January

Due to the findings from past work around stations and the negative population trends in colonies near them, a variable called "station" was included, which was a binary factor (1: if a station was present, or 0: if a station was not present). Note that although Cape Shirreff is not near a field station, it is regularly monitored by researchers and thus we include it in this categorization.

Data standardization

Colony penguin nest counts, and number of passengers landing were standardised to have a mean of 0 and standard deviation of 1, which ensures all data are on the same scale. In terms of this analysis it makes it possible to better compare nest counts to tourism data (Equation I).

{Eq 1} $$Nv = \frac{n - \bar{n}}{\sigma n}$$

In this case, *Nv* is the standardised value, *n* is the nest count, $\bar{n}$ is the mean nest count for the colony, and σn is the standard deviation of the nest counts for the colony. The standardised counts were plotted against the variables in Table 1, however for the purposes of the study only those with relevant patterns are presented.

Trend analysis

To analyse gentoo penguin population trends and compare against tourism parameters, gentoo nest counts were normalised against a global mean value as per Eq. 1. This is termed normalization as opposed to standardization because the data are normalised to a global mean as opposed to standardised to the same scale. Equation I is applied using different values than the standardization method. *Nv* becomes the normalised value, *n* is the original nest count, $\bar{n}$ is the mean of all nest counts across all colonies, and σn is the standard deviation of all nest counts across all colonies.

Normalization is preferred to standardization for looking at trends because trends do not scale with standardization, whereas with normalization, the trend lines scale linearly, meaning they are more comparable to the raw data (i.e., closer to reality).

We calculated population trends using linear regression to get the linear direction of population growth over time. We use the slope of the regression line for the analysis, where positive slopes mean increasing populations, while negative slopes mean declining populations.

Similarly, we use the slope of the linear regression of tourist activities over time to determine if tourist activities are suppressing population growth. This is done by plotting the slopes of the lines against each other. What we look for in this case is whether or not there is a negative relationship between penguin population growth and any tourism parameters.

Predictive analysis

To further explore any impacts of tourism on gentoo penguin nest counts, we

use a predictive analytical approach using a machine learning algorithm called random forests (Breiman 2001). Random forests is a widely used machine learning algorithm that is very powerful for picking out obscure signals in noisy data (i.e., those data that have additional signals or information that cannot be identified by measurable parameters), and can handle missing data (Breiman 2001). The algorithm is implemented using the 'SuperLearner' package in the R programming language.

The goal of this analysis was to see how much variability in the penguin nest count data could be explained by tourism parameters. From the random forests model, relationships between the variables can be extracted and examined, and the importance of each variable in the model is quantified and ranked. The model is only run using visited sites (a total of 21), and the standardised nest counts are used along with the standardised passenger counts to ensure that data are on the same scale which is more appropriate for looking at the relationship to nest counts.

Lag Analysis

To better understand how past or cumulative visitation might affect a change in abundance between census periods, we also modelled normalised nest counts as a function of tourism parameters from both three and five years prior. We used a Generalised Linear Mixed Model (GLMM) framework (lmer, Bates et.al 2015) and compared models for normalised penguin nest count at a given site (i) and year (t) as a function of all possible combinations (15 models were trialled) of four tourism parameters from three years prior (t-3). Tourism parameters included in the model selection process were 1) Median visit time 2) total number of passengers per year 3) median number of pax per visit, and 4) median time ashore.

For all fifteen models, a site variable was included as a random effect. We repeated this routine with a five-year time lag (t-5) to compare a range of generation lengths for Gentoo penguins, which typically span 3–5 years. For both the 3-year and 5-year scenarios, models with all possible variable combinations were run and the best model was chosen based on lowest AIC score.

Results

Gentoo trend analysis

Exploratory analysis of tourism activities and gentoo populations demonstrated some very clear trends; firstly, gentoo penguin populations, except for a few colonies, have been increasing across most of the Antarctic peninsula. Secondly, all metrics of tourism have increased since 2003 and as such a spurious correlation between the median number of passengers and the number of gentoo penguin nests exists (i.e., there is a correlation between increasing number of passengers and increasing gentoo penguin populations however it is not likely a causative correlation).

In general, of the 28 selected colonies, 17 show positive linear trends in the number of counted nests suggesting population growth. The other 11 colonies are showing negative linear trends in the number of counted nests. Data availability was reasonable for most colonies across the 2003–2022 time period except for Skottsberg point (Fig. 2).

Gentoo nest counts versus tourism

Standardised nest counts plotted against tourism parameters did not show many discernible linear patterns (Fig. 3). Following up from past work suggesting impacts from tourism at stations (Trathan et al. 2010, Dunn et al. 2019), the relationships were also plotted for those sites with research stations. No linear relationships were found with the number of landings and the standardised total number of passengers against research stations (Fig. 4). These relationships were also plotted for sites without research stations and no linear patterns were found (Fig. 5).

Linear growth of breeding populations versus linear growth in tourism

Comparing the linear trends of the normalised number of nests over time versus the change in tourism parameters over time may help to identify if linear trends are being depressed in more visited colonies. This helps to examine if population growth varies negatively with growth in tourism. Non-visited sites were removed as well as those with stations (Port Lockroy, Jougla Point, Brown Station and Waterboat Point), limiting the number of confounding factors.

When comparing linear trends in normalised nest counts to linear trends in tourism parameters, there were no discernible patterns. A slight negative trend in the median number of passengers was noted, but there were large confidence intervals around this suggesting a weak relationship (Fig. 7A).

Linear trends in visited versus non-visited sites

Visited sites had a mean normalised linear growth trend that was 57% lower than the mean normalised linear growth rate of non-visited sites. Although there was some overlap in the standard error of the means, it was relatively minimal (Fig. 7).

Model metrics and variable ranks

The random forests model that was run explained 32.51% of the variance in the data, and had a mean squared residual value of 0.62. This means that on average, the predicted standardised nest count was 0.62 from actual standardised counts during the cross validation (model testing) phase.

The most important variables for predicting standardised nest counts were season followed by latitude. The third and fourth most important variables were the standardised median and standardised total number of passengers, followed in fifth by the number of landings (Table 2).

Table 2
Variable ranking from the best random forests model

Rank	Variable	Increase in node purity
1	Season	77.21
2	Latitude (decimal degrees)	46.35
3	Standardised total # of passengers	18.24
4	Standardised median # passengers / season	15.97
5	Total # of landings	8.20
6	Minimum number of passengers	7.66
7	Max. number of PAX landed in December	7.23
8	Max. number of PAX landed in November	6.83
9	Maximum time visited	6.76
10	Median time of visits for season	6.75
11	Mean absolute deviation of PAX in January	6.48
12	Mean absolute deviation of PAX in December	6.29
13	Maximum number of passengers	6.20
14	Median number of PAX in December	5.88
15	Mean absolute deviation of PAX in November	5.82
16	Station present	5.42
17	Median number of PAX in January	5.29
18	Median number of PAX in November	5.21
19	Median time per passenger	4.98
20	Max. number of PAX landed in January	4.75
21	Mean absolute deviation of PAX numbers	4.38

Modelled relationships

Partial dependence plots are ways of explaining the relationship between variables in a model while considering all the other included factors. In Fig. 8C, standardised nest counts were lowest when there were > 75 landings per season. Counter-intuitively, there seems to have been a positive relationship between the nest count and the standardised total number of passengers (Fig. 8B) and standardised median number of passengers (Fig. 8A). In Fig. 8D, it is shown that nest counts tended to be lower when the minimum number of passengers ashore was > 25.

Plotting a three-way relationship of standardised median number of passengers and total number of landings highlights that the lowest nest counts are associated > 75 landings per season, while the effect of standardised median number of passengers is negligible (Fig. 9).

Time-lagged analysis

The best model from both the 3-year and 5-year lag analysis retained number of visits per year as a singular explanatory variable. The 3-year lag model's effect on nest count was positive but insignificant (0.00160, $p = 0.5481$). The 5-year lag model's effect on nest count was negative and insignificant (-0.001818, $p = 0.5135$). This suggests that the population at a generational level is not significantly affected by how often a site is visited three or five years prior. Thus, increasing tourism in Antarctica and increasing nest counts for Gentoos at that site are likely a correlative relationship.

Discussion

The increase in tourism in the WAP region could potentially have profound implications on management of Antarctic penguin populations. In this study, we report on three broad subjects: a) Current gentoo population trends at several key colonies around the WAP region, b) the relationship between several parameters derived from tourism data and gentoo penguin population trends, and c) the use of predictive analytics to determine if tourism data could be used to predict penguin populations and therefore assess whether or not any negative relationships could be elucidated from that analysis.

Gentoo penguin trends

Only 28 colonies were able to be used for this analysis due to the lack of readily available data from other gentoo colonies. However, the colonies make up a reasonable mix of visited and unvisited colonies (21 versus 7 respectively). As has been reported in other work, most linear population trends are positive for gentoo penguins (Ciaputa and Sierakowski 1999; Zhu et al. 2005; Lynch et al. 2012). There were 11 sites that had obvious negative trends were Bryde Island East, Bryde Island South, Cape Shirreff, Danco Island, Dorian Bay, Dorian Becaon, Jougla Point, Neko Harbor, Port Lockroy, Skottsberg Point, and Yankee Harbour. Of those seven, Skottsberg Point and Yankee Harbour (both sites in the South Shetland Islands) were somewhat data deficient compared to other sites, and it is difficult to say if those trends will change with more data collection. Furthermore, both Skottsberg Point and Yankee Harbour have anomalous years with very low nest counts in 2018 and 2015 respectively which might be pulling the trendlines in a negative direction. Several sites also had anomalous low nest counts for many colonies, particularly those in the Gerlache Strait region in the 2021/2022 breeding season (Fig. 2). These counts are contributing significantly to changing trend trajectories of certain colonies (e.g., Neko Harbour, Bryde Island East).

The increase and southward expansion of gentoo penguins has largely been attributed to climate change, which is either opening new breeding sites, or changing food availability in favour of gentoos (Lynch et al 2012, Clucas et al. 2014, McClintock et al 2010). The patterns reported in those and other previous works (e.g., Dunn et al. 2018) follow in line with trends in increasing temperatures and decreasing sea ice across the Antarctic Peninsula. Four notable colonies (Petermann and Pleneau Islands, Biscoe Point and Barton Peninsula) show distinctly linear population growth with limited variability, noting that Lynch et al. (2010) suggested that gentoo penguins at Petermann Island had lower breeding success potentially due to heavier visitation.

Negative population trends for gentoo penguins are unusual as these birds are often referred to as climate change “winners” (Clucas et al. 2014) due to their adaptability (Miller et al. 2009, Hinke et al. 2012). Bryde Island South and Cape Shirreff are sites not visited (or visited very rarely) by tourist vessels, and thus declines at those colonies are unlikely due to any sort of tourist disturbance, indicating other potential factors (e.g., precipitation; Youngflesh 2021).

Comparing nest counts to tourism data

A comparison of the normalised nest counts to tourism parameters demonstrated no specific pattern across all visited sites between the number of counted nests and any of the tourism parameters (see Figs. 3–5). This is in line with other work by Lynch et al (2019), and Youngflesh et al. (2021) suggesting limited impact by visitors on penguin stress levels, or phenology. However, the possibility of cumulative impacts remains, as suggested by Trathan et al. (2008) and Dunn et al. (2018). Both studies suggest that persistent research effort at sites that are popular for tourist visitation may impact penguin productivity. This analysis notes negative linear relationships at research stations between standardised nest counts and the number of landings and median number of passengers. Furthermore, it is notable that the Cape Shirreff colony, another site with persistent research effort, is also experiencing a decline in total nest counts. However, the machine learning analysis did not identify this as a top predictor variable, although the type of research being performed at stations was not considered in this analysis and may be important.

It could be that persistent researcher presence (or types of activities) is influencing breeding performance at specific sites (i.e., Port Lockroy, Jougla Point, or Cape Shirreff), which has been noted in other groups of seabirds (Carey 2009). It may also be that the cumulative impact of tourism and researcher/conservation presence is impacting birds either through nest abandonment or prevention of birds returning to nests. Other top-down effects such as predation after fledging (which can be significant; Hinke et al. 2020) could be exacerbated by tourist visitation or researcher effects whereby chicks are not being fed as frequently, thus leading to reduced fitness prior to fledging. A more comprehensive analysis of gentoo penguins at or near research stations should be carried out to confirm or refute this finding.

Gentoo population trends and tourism trends

Comparison of gentoo population trends and trends in factors derived from tourism data found no obvious linear relationships. Slight negative linear trends were found between gentoo penguin population trends and the median and total number of passengers, but they were relatively insignificant. This suggests that gentoo population growth may be depressed at colonies that are visited with increasing frequency. Therefore, even if the colony is generally growing, it may be growing less rapidly than would be expected without tourist visits. However, this was not a strongly obvious trend and there was some variation around this (see Fig. 6).

A more striking pattern that was found was that the mean linear penguin population growth trend in un-visited sites was higher than the mean linear growth trend in visited sites. There was a small amount of overlap in the standard error bars (high overlap would suggest that the values of the mean could be the same), but this was minimal, which is highly suggestive of a suppression of population growth rates due to tourism activity. The mechanism of this requires further study. The most obvious possibility is that there is some form of direct impact with landings causing disturbance. However, it may be possible that there are less obvious impacts that come from the presence of vessels and related human activities around visitor sites with gentoo penguin colonies or perhaps penguins not being able to return to colonies as effectively after foraging trips due to these activities. There also remains the possibility that these visited sites (often in the Gerlache strait region) may simply have lower growth rates due to environmental reasons (e.g., increased snowfall compared to non-visited sites/regions).

Predictive analysis

For the predictive analysis, a machine learning algorithm (random forests) that is designed to detect complex non-linear patterns in data was used. The particular purpose of this exercise was to determine how much variation could be captured in the data using tourism-based factors. The algorithm does this by trying to predict the target variable (in this case, normalised nest counts) using the predictor variables (i.e., the tourism data).

The model was only able to capture 32.51% of the variation in the standardised nest counts for the visited sites, of which most of that variation was captured in the season parameter. This model was best characterised by the season, location (in degrees latitude), the median and total number of passengers, and the total number of landings per season. Results suggest that although only a small amount of variation is captured, there is a particular set of parameters where penguin nest counts tend to be lower (i.e., when the total number of landings was > 75). Further work on specific behavioural relationships between tourism activity and penguins might help clarify the exact mechanisms for this relationship.

The predictive analysis was not able to discern a meaningful relationship with existence of a station and nest counts in this context. However, there is a need to further examine specific activities at research stations and how they might impact the birds that breed there.

Lagged Effects

Our finding that tourism does not have a significant effect on nest abundance begged the question of whether there was perhaps a time-lagged effect. The generation time of a Gentoo penguin tends to fall between 3–5 years thus impacts of tourism on nesting behaviour and eventually recruitment, might not be detectable for several years. When we examined this relationship, we again could not reject the null hypothesis that tourism did not affect nest abundance three to five years in the future. However, given tourism's increasing volume, it is going to be important to monitor this relationship as this effect may become a more important predictor of gentoo penguin abundance with time.

Climate change and other impacts

Climate change was not included as a factor in this analysis partly due to a mismatch in scale for readily available data (i.e., downloading, processing and managing fine-scaled temperature and sea-ice data is a time-intensive task that fell out of the available time for this body of work, leaving only coarse scaled temperature data which would not capture individual variability at each site). Primarily, the goal of this work was to examine the role of tourism activities on penguin populations and the type of predictive analysis that was used allows this to occur without including climate change as a factor. This is because the algorithm is looking for specific patterns in the predictor variables which will contribute to best predicting the target (i.e., the normalised nest count). The patterns that are presented in Figs. 8 and 9 are the ones that best contribute to predicting the normalised nest counts, and inclusion of any other factors will not change that relationship. The inclusion of a climate change parameter would only tell us if climate change were a better predictor of nest counts than tourism factors. However, declining populations that are being detected at places like Cape Shirreff warrant further consideration as there could be localised shifting food web dynamics or other forms of disturbance (e.g., climate change effects). It may even be possible that immigration and emigration are factors in determining colony growth or decline, but it is difficult to measure those factors, and upcoming genetic work may give some insight into this.

The other potentially important impact on colony growth is carrying capacity, which was also not included in this analysis as it requires strict definitions of this concept in relation to nesting area or resource availability, which was not available for inclusion. Smaller sites with less nesting area available might be more susceptible to declines or slowed colony growth overall.

Future work

In general, there are many open questions regarding tourism impacts on penguins. This analysis extends from 2003–2022, yet the 2022/2023 field season was the most visited year since tourism began with over 109,000 tourists in the WAP; a trend which continued into the 2023/2024 season. Gentoo penguins are a unique and interesting case in the WAP region because of their expanding populations. Because of this, the larger question that needs to be examined is whether tourism is slowing gentoo population growth. In the future, there are several analyses that should be undertaken:

1. A more comprehensive examination of the "researcher effect" and whether stations or researchers are having adverse effects on gentoo population growth.
2. Categorization and study of specific passenger impacts at the colony level (i.e., detailed observations of any behaviours, however small, that are being disrupted by tourists or ships) to help

identify any mechanisms of disruption.

3. A site-by-site examination of the identified negative relationships (e.g., number of landings) to identify specific sites for further non-invasive observational work
4. A comparison with heavily visited Adélie or Chinstrap penguin breeding colonies.
5. A spatial analysis comparing sites and exposure to passengers (e.g., some colonies might have more exposure to passengers because they are smaller sites). This would also include an analysis of colony carrying capacity and access points which could be blocked or restricted due to passenger traffic.

Conclusions

This study characterises the relationship between tourism activities and 28 gentoo penguin sites around the Western Antarctic Peninsula region. This analysis found that gentoo penguin population growth may be depressed at colonies that are visited with increasing frequency; in other words, that even if gentoo colonies at some popular visitor sites are generally growing, they may be growing less rapidly than would be expected without tourist visits. Further work would help to identify the specific mechanism for this difference. A predictive machine learning algorithm was also used to potentially detect other complex patterns, however no obvious meaningful relationships were identified, and a lagged analysis of the effects of tourism on nest counts also led to no significant statistical connections. The suggested future work could help determine any possible mechanisms for the patterns found in this study which will inevitably help determine if and how tourism activities impact gentoo population trends in the WAP.

Declarations

Author contributions:

GH and RN conceived and designed the research. GH and LB performed analyses and contributed to the writing of the manuscript. Tourism data were provided by the International Association of Antarctica Tour Operators (IAATO). IAATO provided input to the writing of the manuscript and design of the research. All authors have read and approved the manuscript.

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Data Availability

Tourism Data were obtained from IAATO under an NDA and MOU. Penguin population data were obtained from the open-access database, MAPPPD, which is found at www.penguinmap.com.

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Figures

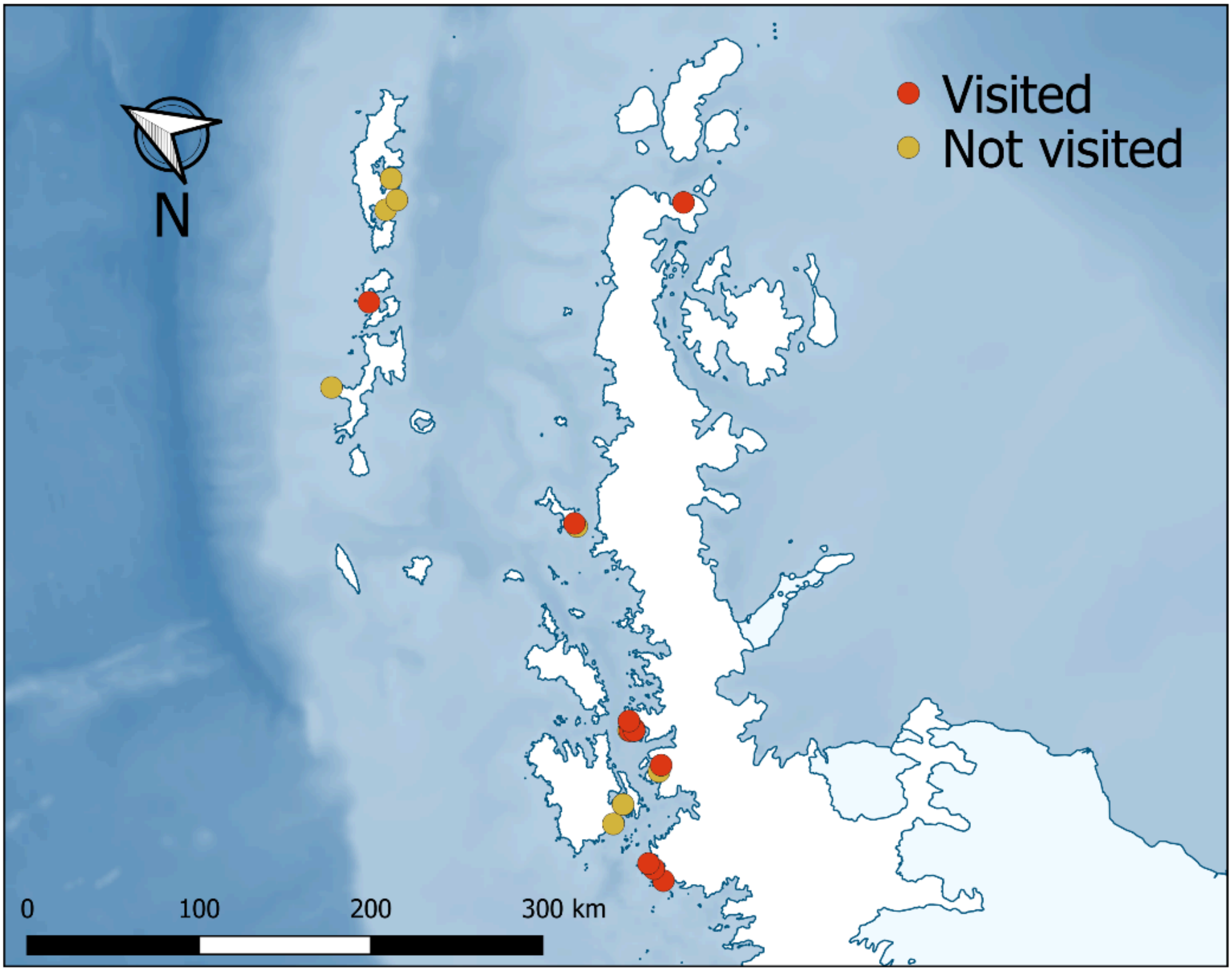

Figure 1

Sites selected for analysis categorized by "visited" and "not visited" by tourists from the 2003 - 2021seasons

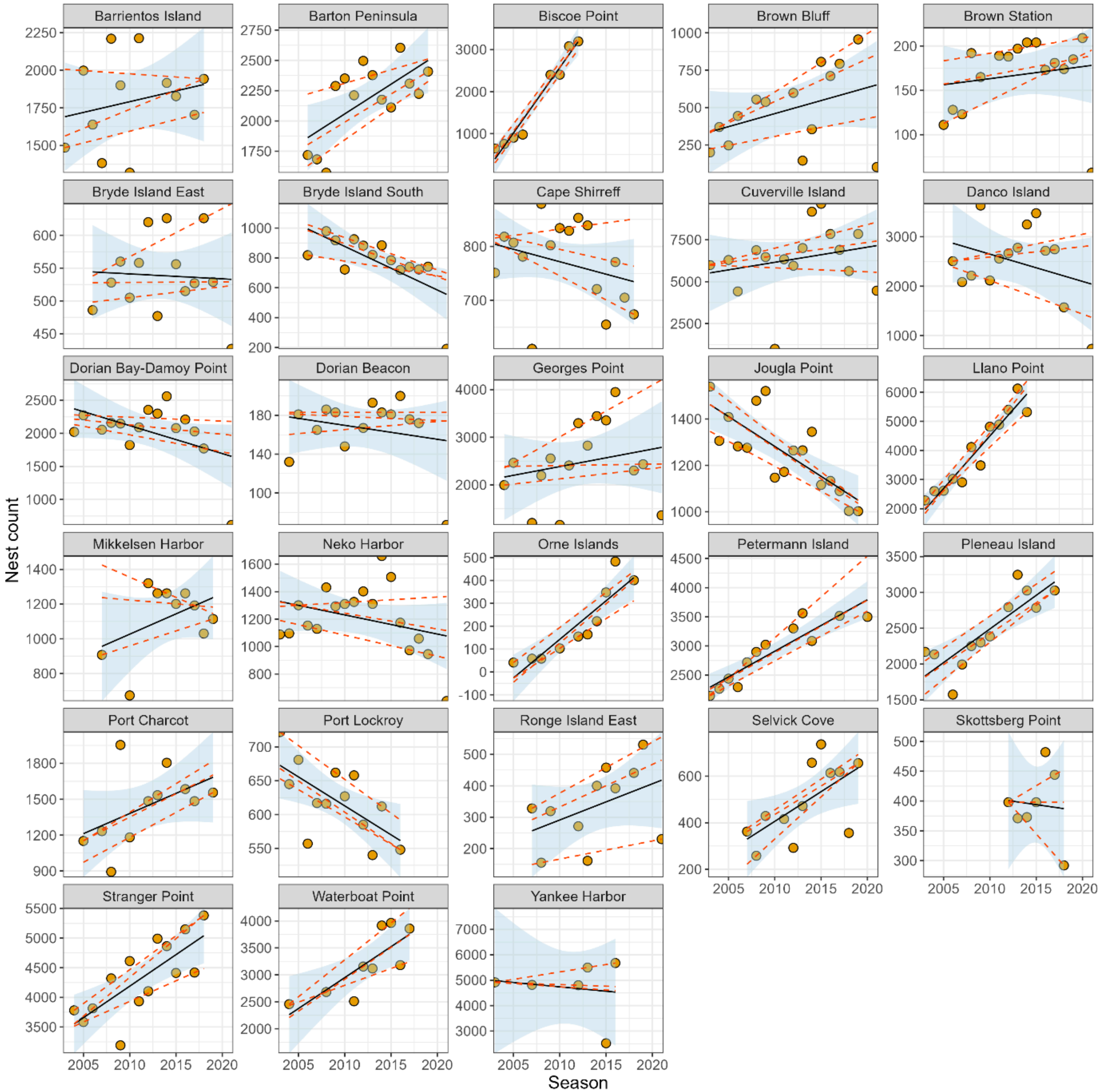

Figure 2

Gentoo penguin nest counts from the MAPPPD database for colonies with > 6 records (representing the top 25th percentile of total site counts). The black trend line and blue shading represent a linear model and 95% CI, and the red dashed lines indicate quantile regressions for each of the 0.25, 0.5, and 0.75 data quantiles.

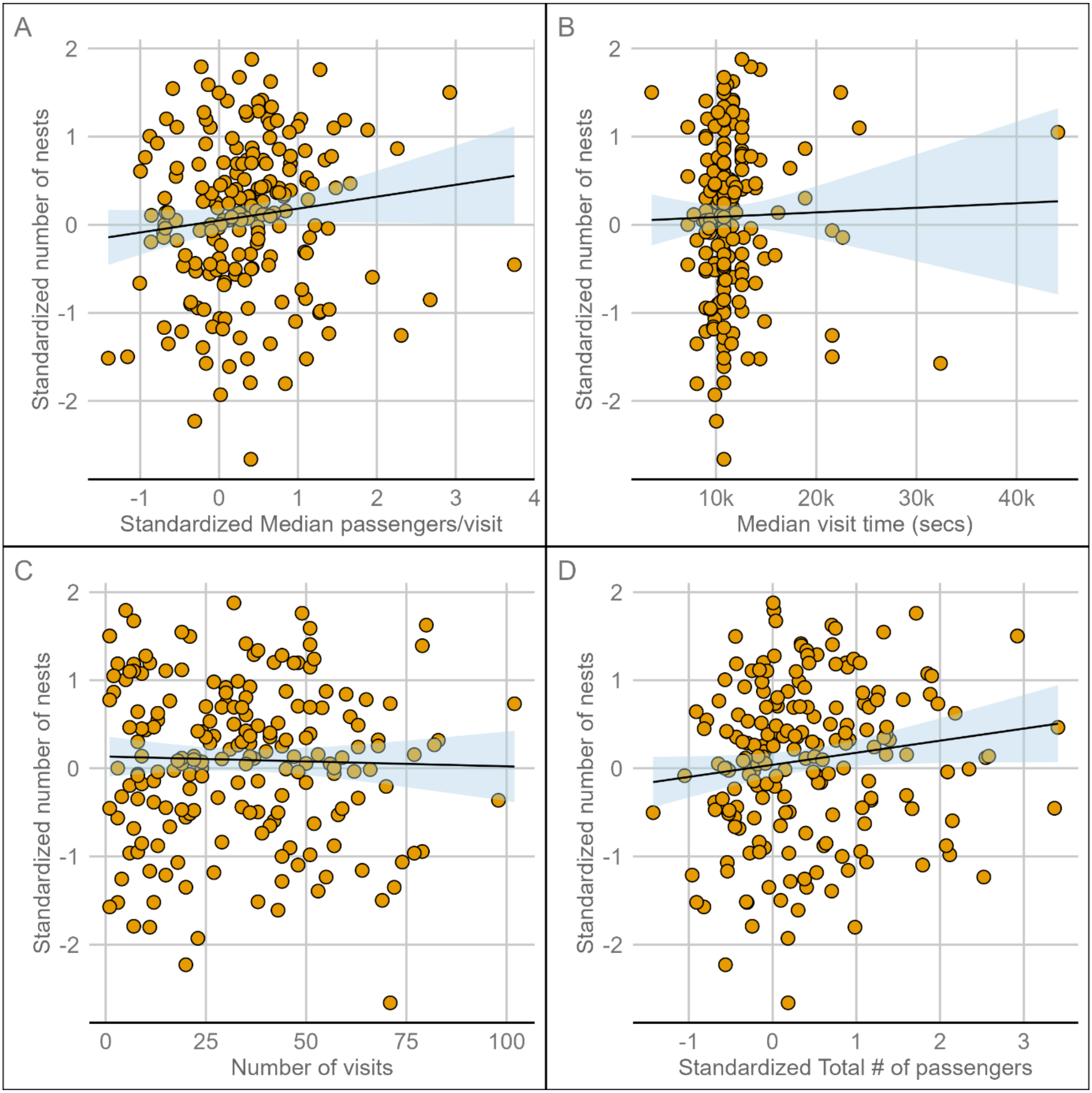

Figure 3

Standardised gentoo nest counts for all sites plotted against tourism parameters derived from IAATO data. Trend lines showing the relationship are also plotted.

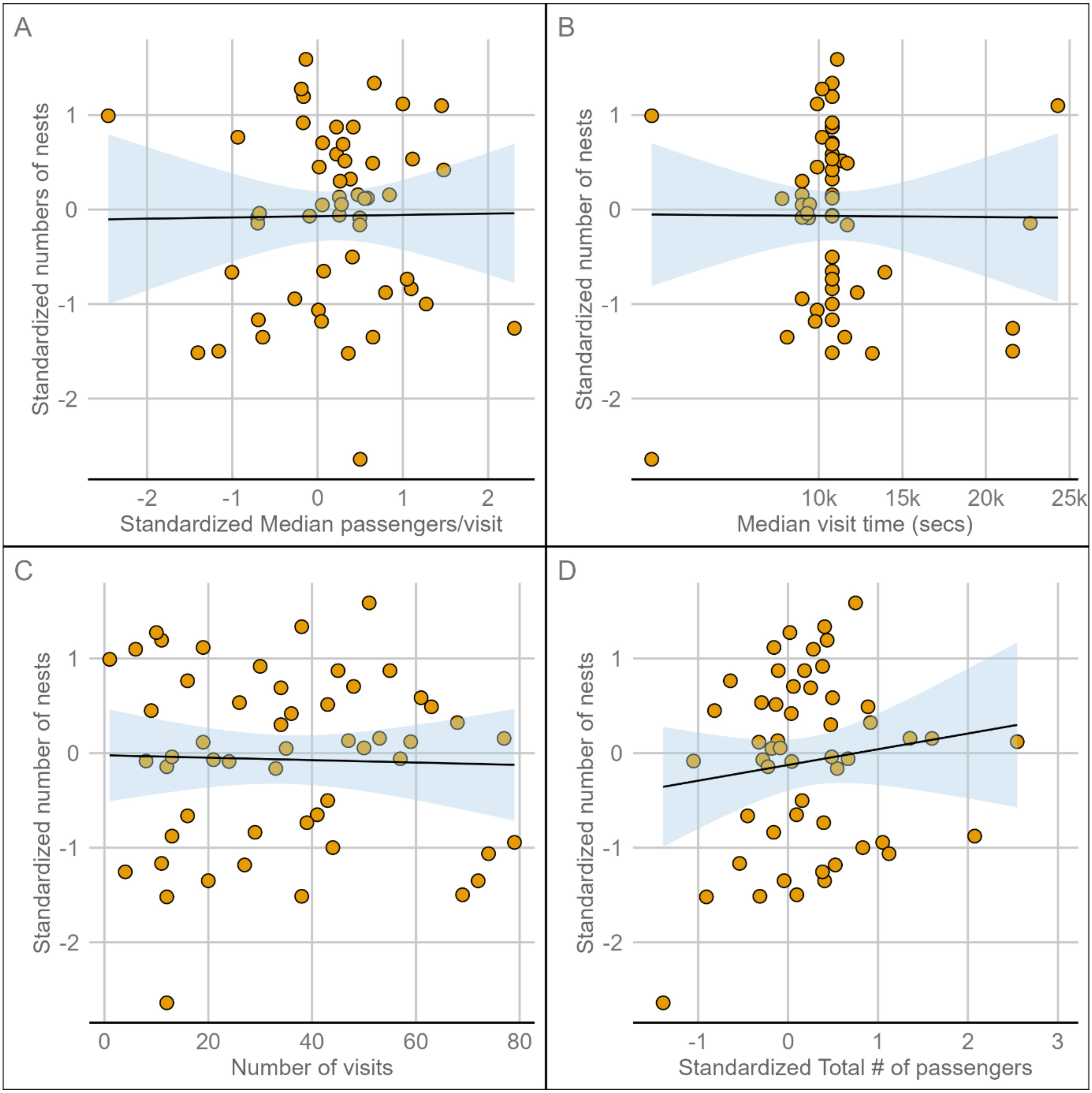

Figure 4

Standardised gentoo nest counts for all visited colonies on or within 500m of a research station (Port Lockroy, Jougla Point, Brown Station, and Waterboat Point) plotted against tourism parameters derived from IAATO data. Trend lines showing the relationship are also plotted.

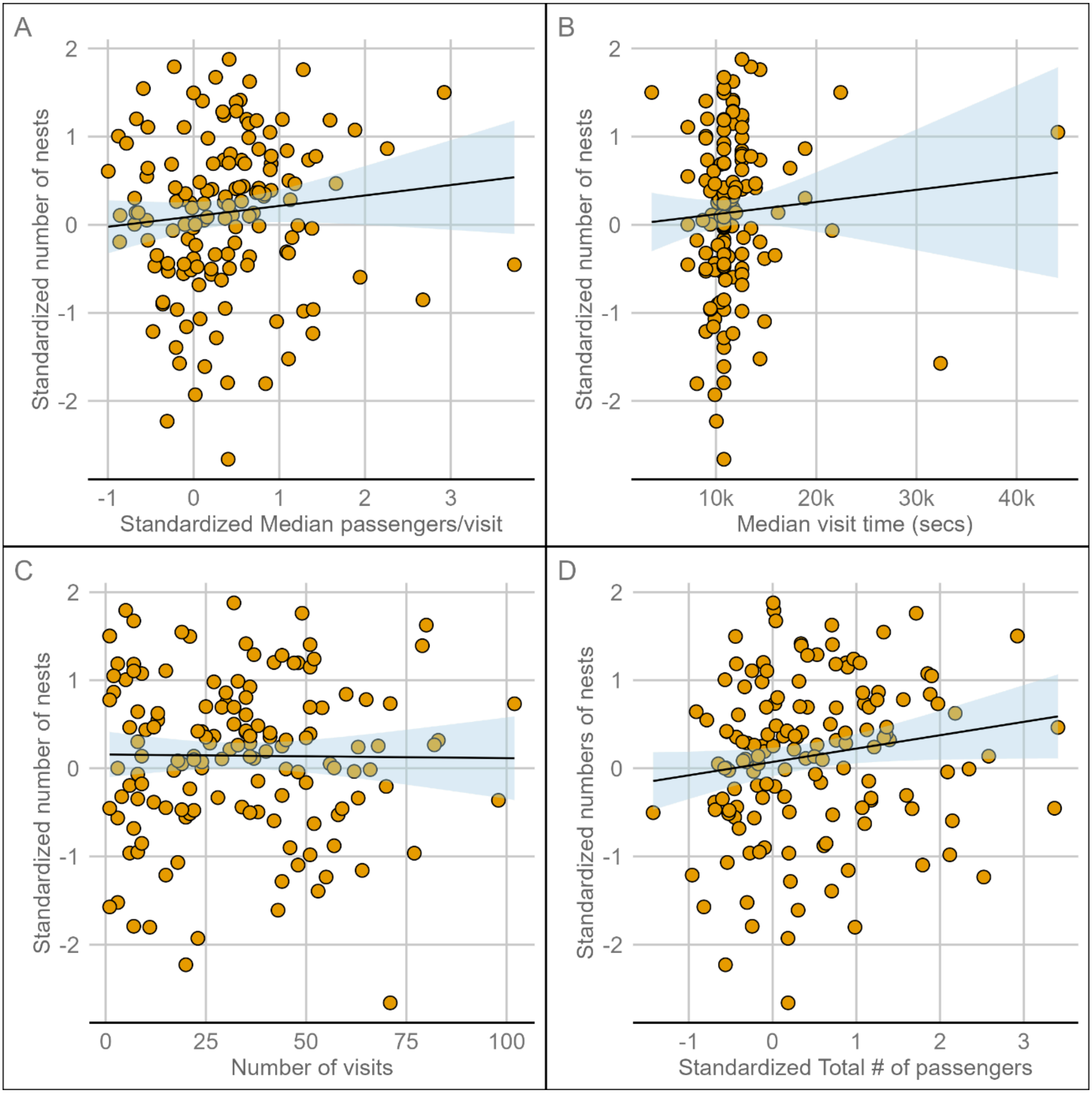

Figure 5

Standardised gentoo nest counts for all sites except Port Lockroy, Jougla Point, Brown Station, and Waterboat Point plotted against tourism parameters derived from IAATO data. Trend lines showing the relationship are also plotted.

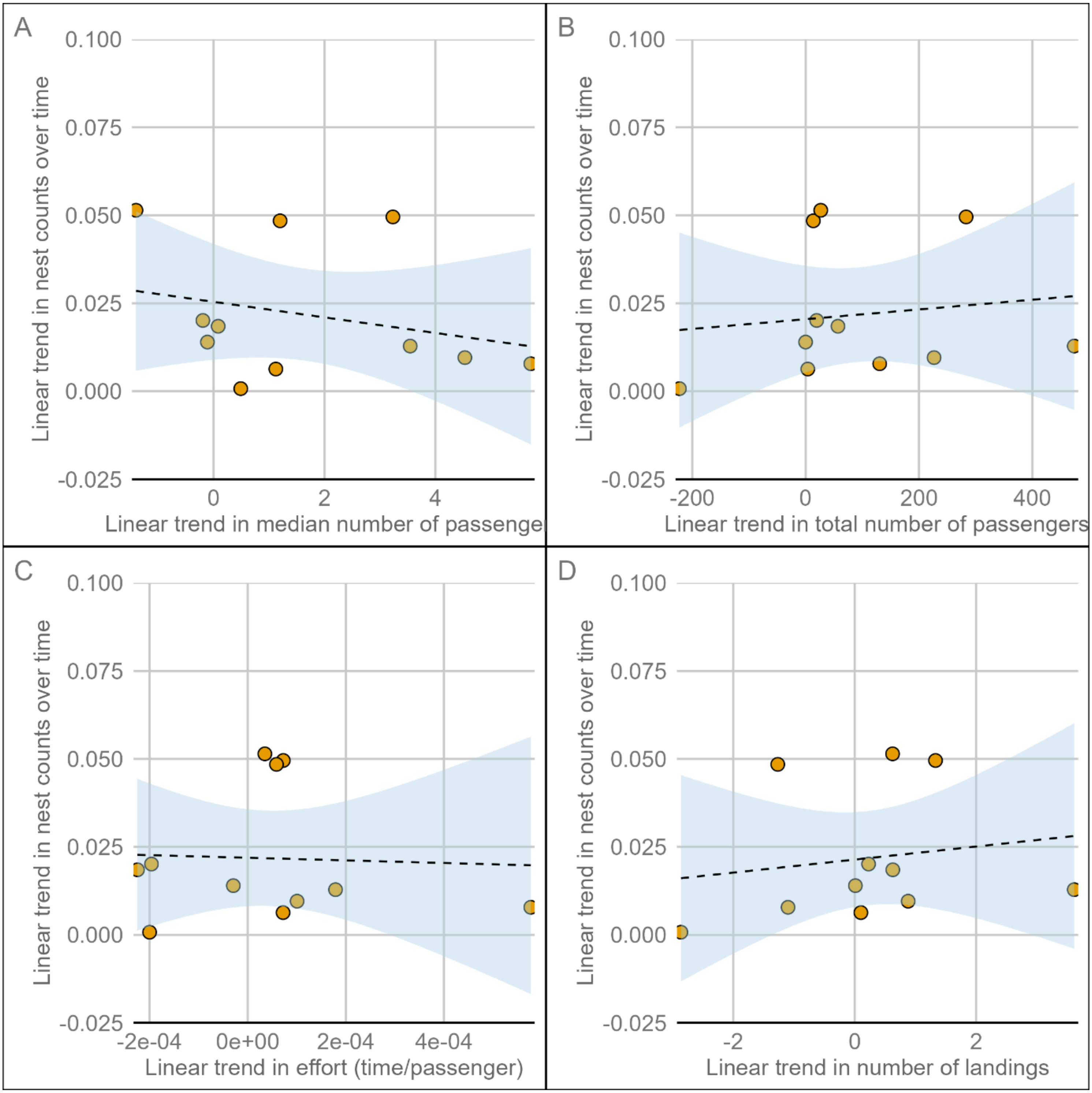

Figure 6

Comparison of linear trends of normalised gentoo nest counts for visited colonies (except for those with stations), versus the linear trend in tourism parameters.

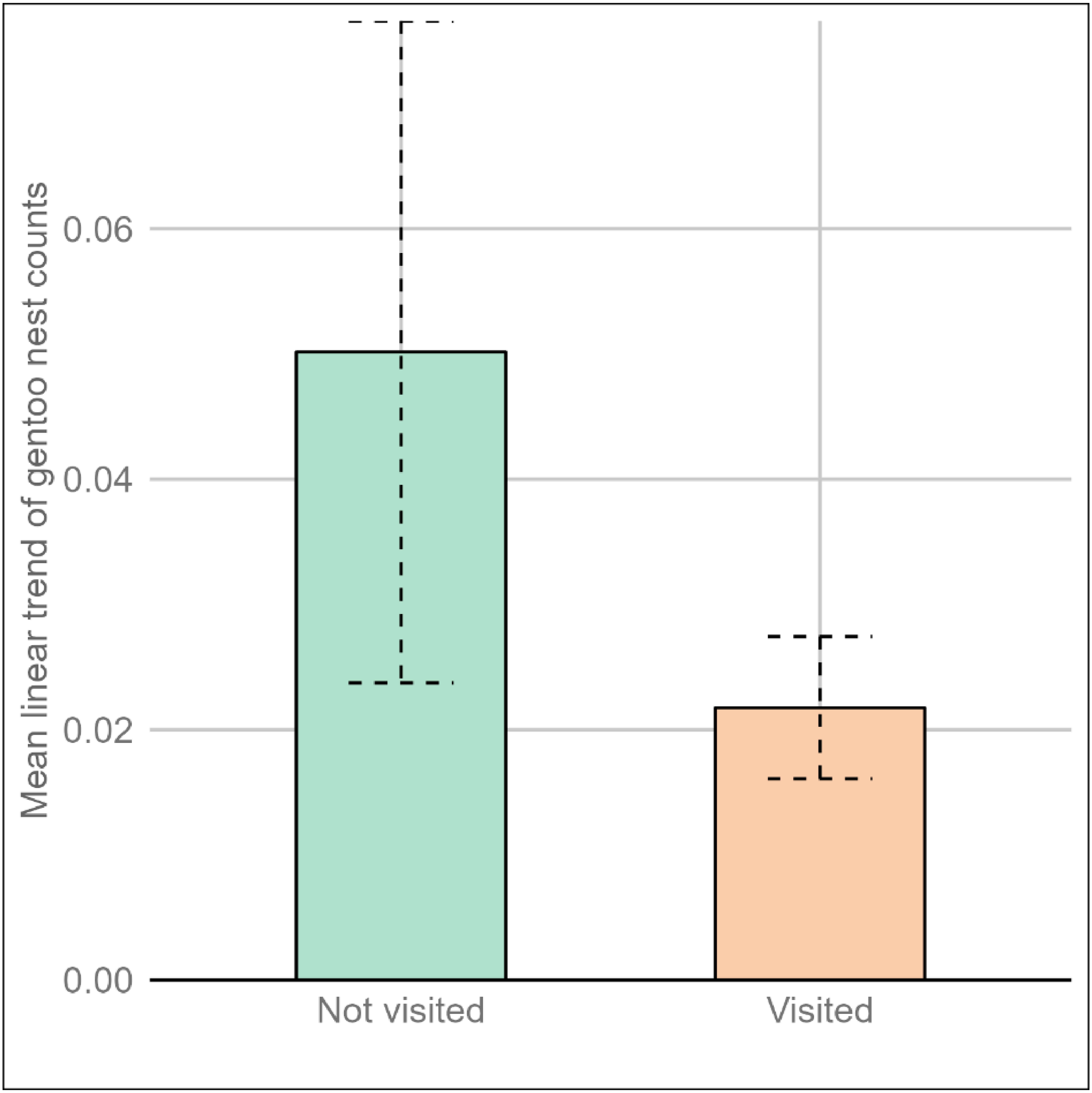

Figure 7

Mean linear trends (and standard error) of linear trends of gentoo penguin nest counts over time for visited (19) and not visited sites (7).

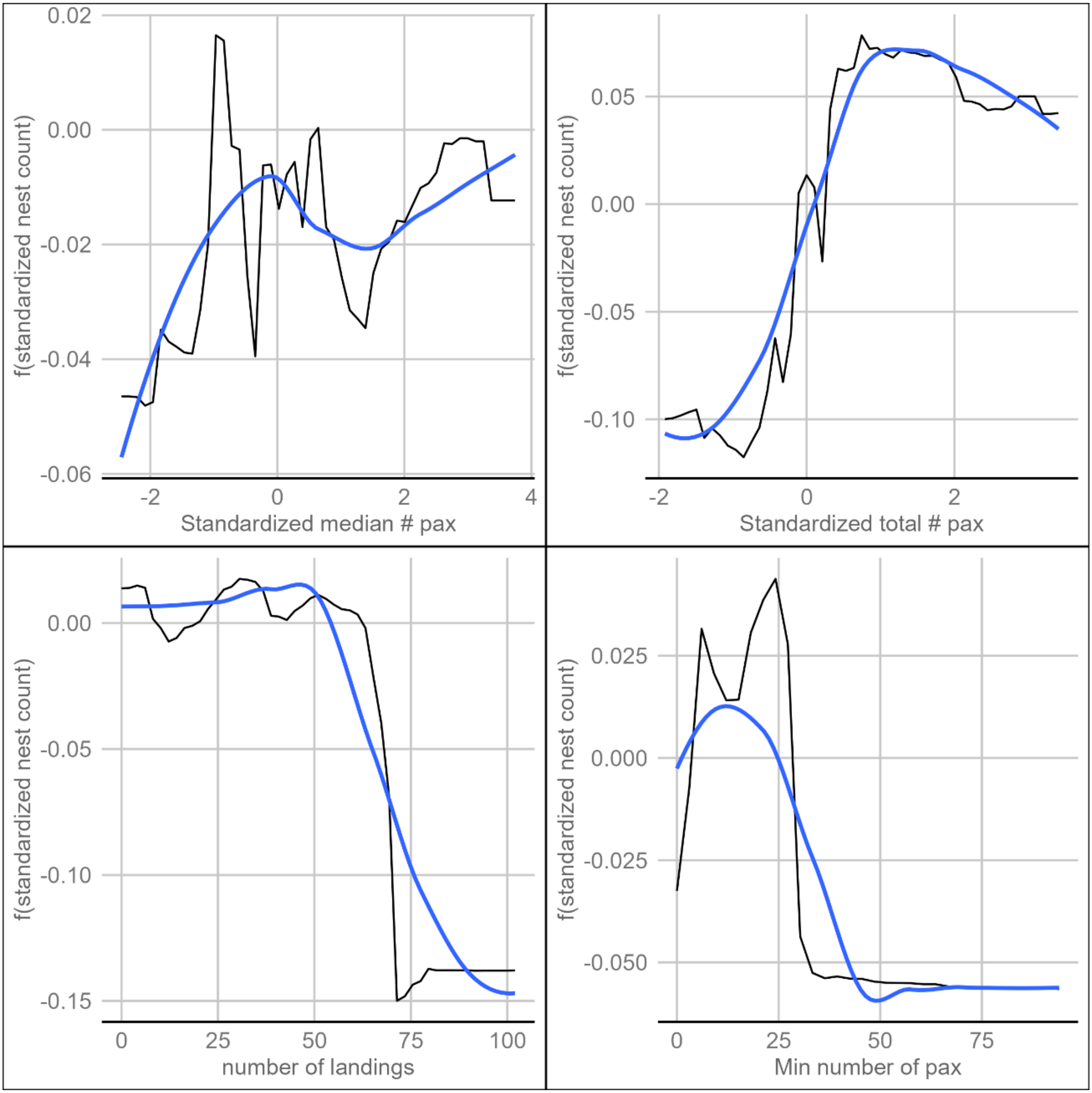

Figure 8

Partial dependence plots of the standardised median of passengers, standardised total number of passengers, number of landings and minimum number of passengers in relation to the standardised nest counts. Blue lines indicate a loess curve, and black lines indicate partial dependence function.

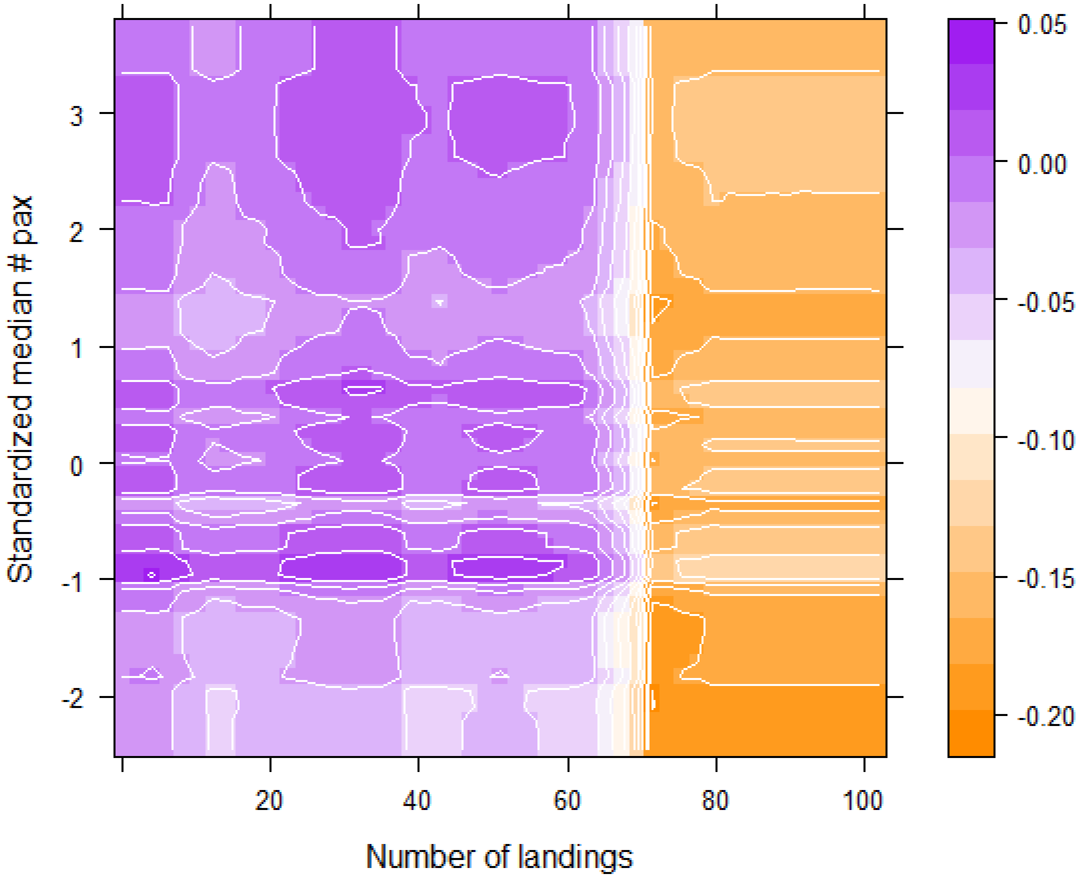

Figure 9

Three-way plot of standardised median number of passengers, number of landings and the partial dependence of the standardised number of nests (Orange to purple colouring).