

Wrack as a Roughness Element: Nonlinear Effects on Airflow and Sediment Deposition in a Coastal Dune System

Phillip P. Schmutz^{a*}, Samantha R. Seals^b, Joseph Agin^a, and Peter A. Tereszkiewicz^c

^a Department of Earth and Environmental Sciences, University of West Florida, 11000 University Parkway, Pensacola, FL 32514, USA

^b Department of Mathematics and Statistics, University of West Florida, 11000 University Parkway, Pensacola, FL 32514, USA

^c Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center, 3909 Halls Ferry Road, Vicksburg, MS 39180, USA

*Corresponding author:

Phillip P. Schmutz

Department of Earth and Environmental Sciences

University of West Florida

11000 University Parkway

Pensacola, FL 32514, USA

Email: pschmutz@uwf.edu

Author contributions:

- Phillip P. Schmutz:
 - Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing
- Samantha R. Seals:
 - Formal analysis, Methodology, Validation, Visualization, Writing – review and editing
- Joseph Agin:
 - Conceptualization, Data curation, Methodology, Investigation, Writing – original draft, Writing – review and editing
- Peter A Tereszkiewicz:
 - Conceptualization, Methodology, Supervision, Writing – review and editing

Manuscript is a non-peer reviewed preprint.

Abstract

Coastal dunes are shaped by interactions among wind, sediment supply, and surface roughness elements. While vegetation is widely recognized as a driver of aeolian sediment dynamics, beach wrack remains understudied despite its frequent occurrence on sandy coastlines. This study investigated how wrack modifies airflow and influences sediment deposition. Paired 2D anemometers positioned upwind and downwind of a natural wrack pile and a single-point terrestrial LiDAR were used to quantify wind reduction and bed-level change. Generalized linear models (GLMs) and generalized additive models (GAMs) were used to evaluate relationships among wind speed, wind angle, wind reduction, and sediment deposition. Wind speed and wind angle significantly influenced wind reduction ($p < 0.001$), with the GAM providing a significantly better fit than the GLM ($\Delta AIC = 612.7$; $p < 0.001$). Wind reduction increased with wind speed and varied according to wind orientation, indicating that wrack functions as a dynamic aerodynamic roughness element. Wind speed and wind angle also significantly influenced sediment deposition dynamics, although depositional responses exhibited complex nonlinear patterns and substantial variation. For both airflow reduction and sediment deposition, the GAM identified relationships that were oversimplified or undetected under linear assumptions. Overall, these findings demonstrate that wrack significantly modifies local airflow and creates conditions favorable for sediment retention. More broadly, the results suggest that wrack functions as a condition-dependent geomorphic agent whose influence on aeolian transport varies across environmental scales. The study highlights the importance of nonlinear approaches for characterizing aeolian processes and identifying threshold-dependent responses within coastal sediment transport systems.

Keywords: Beach wrack, Aeolian sediment transport, Aerodynamic surface roughness, Sediment deposition, Nonlinear modeling

Running Header: Wrack Effects on Airflow and Deposition

Highlights:

- Beach wrack significantly modified local airflow patterns
- Wrack acted as a dynamic, condition-dependent roughness element
- Wind speed and angle controlled airflow reduction and deposition
- GAMs identified nonlinear responses overlooked by linear models

Introduction

Coastal dunes are dynamic landforms that develop through interactions among wind, waves, sediment supply, vegetation, and other surface roughness elements (Hesp, 2002). Beyond their geomorphic significance, dunes provide critical ecosystem services, including protection from storm surge, wave attack, and coastal erosion (Martínez et al., 2008; Feagin et al., 2015; Temmerman et al., 2013). These functions are particularly important along low-lying coastlines where hurricanes and other severe storms frequently reshape beach-dune systems (Houser, 2009; Houser et al., 2015). Storm events can remove large volumes of sediment from dunes within hours or days, redistributing material across the beach and nearshore environment and fundamentally altering coastal morphology (Guillén et al., 1999).

The persistence of coastal dunes depends not only on their ability to withstand storm impacts but also on their capacity to recover following disturbance. Coastal resilience is often defined as the ability of a system to absorb disturbance while maintaining or recovering essential structure and function (Holling, 1973; Folke, 2006; Masselink and Lazarus, 2019). Beach-dune systems therefore operate through recurring cycles of storm-driven erosion and post-storm recovery (Houser, 2009; Houser et al., 2015; Durán Vinent et al., 2021). Immediately following storms, recovery is often driven by landward beach accretion associated with nearshore bar welding and berm rebuilding (Guillén et al., 1999; Houser et al., 2008; Houser and Hamilton, 2009). Over intermediate timescales, aeolian sediment transport fills erosional scarps, promotes dune ramp development, and gradually restores dune elevations (Houser, 2009; Walker et al., 2017). As recovery progresses, vegetation establishment strengthens positive feedbacks between sediment deposition and plant growth, contributing to long-term dune stability and resilience (Durán Vinent and Moore, 2015; Durán Vinent et al., 2021; Rinaldo et al., 2021).

These recovery processes are governed by biogeomorphic feedbacks in which biological and physical processes interact to influence landform development (Corenblit et al., 2011). As sediment accumulates around roughness elements, elevations increase, creating conditions that promote additional sediment retention and vegetation establishment (Hesp, 1989; Baas, 2002; Hesp, 2002). Through time, these feedbacks reinforce dune growth, increase topographic complexity, and contribute to landscape recovery (Durán Vinent and Moore, 2015; Durán Vinent et al., 2021; Rinaldo et al., 2021).

A fundamental control on aeolian sediment transport during dune recovery is the presence of surface roughness elements that modify airflow and interrupt sediment transport pathways. Natural roughness elements such as vegetation and woody debris as well as artificial structures including sand fences, alter near-surface airflow through drag generation, flow separation, turbulence production, and wake development (Hotta et al., 1987; Raupach, 1992; Lancaster, 1995; Eamer and Walker, 2010; Li and Sherman 2015; Grilliot et al., 2019; Itzkin et al., 2019). Consequently, these aerodynamic effects reduce transport capacity and promote sediment deposition and thus are important controls on dune initiation, recovery, and long-term landscape evolution and stability (Walker and Barrie; 2006; Durán Vinent and Moore, 2015; Rinaldo et al., 2021). Extensive restoration efforts increasingly utilize both artificial and natural roughness elements to accelerate post-storm recovery and enhance coastal resilience (Jackson and Nordstrom, 2011; Nordstrom et al., 2012; Farrell et al., 2023; Tereszkievicz et al., 2025).

Among natural roughness elements used to promote sediment retention and dune recovery, beach wrack has received comparatively little attention in aeolian research despite growing evidence that it can modify airflow, influence sediment transport, and contribute to dune development (Provost et al., 2022 a,b; Tereszkievicz et al., 2025; Tereszkievicz and Ellis,

2025). From an aeolian perspective, wrack functions as a natural roughness element capable of modifying airflow and sediment transport pathways in a manner similar to vegetation. Although wrack lacks the permanence and structural complexity of established vegetation, its accumulation along the beach surface can generate localized zones of aerodynamic sheltering that reduce transport capacity and facilitate sediment deposition (Hemminga and Nieuwenhuize, 1990; Nordstrom et al. 2007; Dugan and Hubbard, 2010; Nordstrom et al., 2011 a,b; Nordstrom et al., 2012).

Beach wrack consists of organic material deposited along the high-tide line, including rhizomes, reeds, roots, marsh vegetation, kelp, and seagrass (Hemminga and Nieuwenhuize 1990). Across disciplines, wrack is also referred to as beach-cast, drift lines, drift piles, detritus, phytodetritus, strandlines, litter, banquettes, and shore drift (Tereszkiewicz and Ellis, 2025). Regardless of terminology, wrack serves as a linkage between marine and terrestrial systems by transferring organic material, nutrients, and physical structure across ecosystem boundaries (McLachlan and McGwynne, 1986; McGwynne et al., 1988; Polis et al., 1997; Barreiro et al., 2011; Mellbrand et al., 2011; Breithaupt et al., 2019; Hyndes et al., 2022). Seasonal storms and energetic wave events transport wrack from subaqueous environments onto beaches, where its residence time is influenced by wrack type, buoyancy, and depositional position (Orr et al., 2005; Oldham et al., 2014).

Despite its natural role in coastal systems, wrack is often perceived as undesirable by beach users and has been associated with concerns related to aesthetics, odors, and potential pathogens (Robbe et al., 2021). As a result, wrack is routinely removed in many coastal communities, particularly those whose economies rely heavily on tourism, to maintain beach aesthetics and address perceived public health concerns (Williams and Feagin, 2010; Jackson

and Nordstrom, 2013; Webster and Linton, 2013; Russell et al., 2014). However, despite its frequent classification as a nuisance, wrack provides important ecological and geomorphic functions by promoting aeolian landform development and nutrient cycling within otherwise nutrient-poor beach–dune environments (Provost et al., 2022a,b; Tereszkievicz et al., 2005). Consequently, growing evidence suggests that wrack can be incorporated into beach management strategies to enhance dune development, recovery, and ecosystem function within beach–dune systems (Williams and Feagin, 2010; Sigren et al., 2014; Robbe et al., 2021; Provost et al., 2022a,b).

Beyond its ecological and management implications, evidence for the geomorphic importance of wrack within coastal science continues to emerge. Nordstrom et al. (2011a) reported reductions in wind speed of up to 11% and documented rapid sediment infilling associated with wrack accumulations. Furthermore, Nordstrom et al. (2012) demonstrated that beaches where wrack was retained developed larger dunes and greater vegetation cover than beaches where wrack was removed. Deposition may occur as either single-stage or multi-stage processes depending on vegetation establishment and continued reductions in airflow (Tereszkiewicz and Ellis, 2025). Buried wrack also decomposes more slowly than exposed material, preserving organic matter and nutrient resources that may facilitate subsequent vegetation colonization (Williams and Feagin 2010; Dugan et al. 2011; Feagin et al., 2015; Egmond et al., 2019; Hooton et al., 2019).

Collectively, these findings suggest that wrack functions as a temporary geomorphic agent during the early stages of dune recovery by trapping sediment, creating localized topographic irregularities, and establishing conditions favorable for vegetation colonization. Consequently, wrack may serve as an intermediary component linking short-term sediment

transport processes with longer-term ecological and geomorphic recovery (Barreiro et al., 2011; Nordstrom et al., 2012; Ruiz-Delgado et al., 2016; Innocenti et al., 2018; Hyndes et al., 2022; Tereszkiwicz and Ellis, 2025).

Despite growing recognition of wrack as an important component of beach–dune systems, our understanding of the small-scale processes through which wrack modifies airflow and influences sediment deposition remains incomplete. This gap is particularly notable given recent syntheses of coastal dune science that identify the parameterization of airflow and sediment transport within roughness-element environments as a major research challenge (Ellis and Sherman, 2013; Hesp and Walker, 2013; Walker et al., 2017; Telfer, 2022; Walker et al., 2022; Farrell et al., 2023). These challenges arise in part due to the inherently nonlinear nature of aeolian systems as sediment entrainment occurs only after threshold conditions are exceeded, transport rates often increase disproportionately with increasing wind velocity, and depositional responses emerge when transport capacity falls below critical thresholds (Baas, 2007). Compounding this challenge is that nonlinear responses have been documented for aerodynamic responses within roughness-elements. Studies have shown that airflow modification within roughness-element environments is governed by complex interactions among obstacle structure, wind velocity, wind direction, turbulence generation, sediment availability, and bed surface conditions suggesting that their influence on airflow and sediment transport processes may vary substantially across environmental gradients (Raupach, 1992; Wolfe and Nickling, 1993; Lancaster and Baas, 1998; Baas, 2002; Okin, 2008; Telfer, 2022; Schmutz et al., 2025). Consequently, the mechanisms through which wrack influences aeolian dynamics and sediment deposition remain difficult to quantify and predict under field conditions. Furthermore, the extent to which these relationships exhibit nonlinear behavior remains largely unexplored.

While contemporary discussions of dune recovery and nature-based coastal protection focus primarily on vegetation, the role of wrack as a near-surface roughness element remains largely absent from conceptual and modeling frameworks (van Dijk et al., 1999; Baas and Nield, 2007; Durán Vinent and Moore, 2015; Durán Vinent et al., 2021; Farrell et al., 2023). Likewise, although wrack is increasingly incorporated into coastal management practices, its role in dune development remains insufficiently documented as a nature-based solution for enhancing coastal resilience under climate change (Temmerman et al., 2013; Farrell et al., 2023). Addressing this gap requires a process-based understanding of how wrack modifies airflow and sediment deposition across a range of environmental conditions.

To better understand the role that wrack plays in coastal dune systems, this research analyzed the effect of beach wrack on wind flow conditions, including velocity and direction, and sediment deposition within wrack accumulations. Specifically, the objectives of this study were to: 1) quantify how wrack modifies near-surface airflow across varying wind speeds and directions; 2) determine how wrack-induced modifications to airflow influence patterns of sediment deposition and erosion; and 3) compare GLM and GAM frameworks to better characterize airflow and sediment transport responses around wrack. Results from this research will improve understanding of how wrack promotes sediment retention, supports dune recovery, and enhances coastal resilience.

Methods

Field research was conducted within a dune blowout system located on the western portion of Santa Rosa Island, Florida (30.3460° N, -87.0701° W). The study aimed to evaluate the influence of beach-cast wrack on near-surface wind dynamics and sediment deposition. A

combination of two-dimensional (2D) anemometers and a single-point terrestrial LiDAR sensor was employed to characterize wind speed and deposition in the vicinity of a wrack pile composed of *Sargassum natans* (Figure 1). The round shaped wrack structure measured approximately 15 cm in height and 25 cm in diameter. Anemometers were positioned 15 cm above the bed surface, and 50 cm upwind and 50 cm downwind of the wrack pile to assess spatial differences in wind speed. The instrument array was aligned parallel to the throat of a dune blowout at an azimuth of 121°. The LiDAR unit was mounted at an elevation of 50 cm above the bed immediately upwind of the wrack to quantify temporal rates of deposition under variable wind conditions. Placement at the wrack interface was intended to capture sediment accumulation associated with transport interception by the wrack feature. Nordstrom et al. (2007) reported substantially lower transport rates downwind of wrack accumulations relative to upwind conditions, whereas transport rates measured across gaps in the wrack line remained unchanged, suggesting that wrack functions as a localized sediment trap and promotes deposition at the transport–obstacle interface.

All sensors were connected to a data logger and recorded at a frequency of 1-Hz. Multiple field deployments were conducted during the study period, each utilizing freshly collected wrack material, to account for variability in aerodynamic and depositional responses associated with wrack morphology and wind conditions.

To reduce high-frequency noise and enhance signal quality, all data were first preprocessed using a 10-second Gaussian filter. Wind reduction was then calculated as the percentage difference between upwind and downwind anemometers.

Wind reduction and sediment deposition were modeled as a function of wind speed and wind angle. Each response variable was examined under two modeling frameworks: 1)

generalized linear models (GLMs) and 2) generalized additive models (GAMs), which are semi-parametric extensions of GLMs that accommodate nonlinear relationships between predictors and the response (Wood, 2017). To ensure comparability between GLMs and GAMs, maximum likelihood (ML) estimation was used in place of restricted maximum likelihood (REML) estimation.

Wind reduction is a continuous outcome modeled using the normal distribution. The generic form of GLM for a continuous outcome is

$$\hat{y} = \beta_0 + \beta_1 x_1 + \dots + \beta_k x_k,$$

while the generic form of GAM for a continuous outcome is

$$\hat{y} = \beta_0 + s(x_1) + \dots + s(x_k).$$

In both the GLM and GAM, y is the outcome of interest, β_0 is the y intercept, and x_i are the predictor variables specified in the model. Under the GLM, β_i are linear regression coefficients that quantify the relationship between x_i and y after adjusting for all other predictors. Under the GAM, $s(x_i)$, is a spline smoothing function that captures nonlinear relationship between x_i and y after adjusting for all other predictors.

Wrack deposition is a multinomial outcome with three possibilities (increase, decrease, and no change). The generic form of GLM for a multinomial outcome is

$$\ln\left(\frac{\hat{\pi}_j}{\hat{\pi}_{ref}}\right) = \beta_{0j} + \beta_{1j} x_1 + \dots + \beta_{kj} x_k,$$

while the generic form of GAM for a multinomial outcome is

$$\ln\left(\frac{\hat{\pi}_j}{\hat{\pi}_{ref}}\right) = \beta_{0j} + s(x_1)_j + \dots + s(x_k)_j.$$

Modeling wrack deposition results in two joint models. Under GLM,

$$\ln\left(\frac{\hat{\pi}_{increase}}{\hat{\pi}_{no\ change}}\right) = \beta_{0(increase)} + \beta_{1(increase)} x_1 + \dots + \beta_{k(increase)} x_k$$

$$\ln\left(\frac{\hat{\pi}_{decrease}}{\hat{\pi}_{no\ change}}\right) = \beta_{0(decrease)} + \beta_{1(decrease)}x_1 + \dots + \beta_{k(decrease)}x_k,$$

compared to the GAM framework,

$$\ln\left(\frac{\hat{\pi}_{increase}}{\hat{\pi}_{no\ change}}\right) = \beta_{0(increase)} + s_{increase}(x_1) + \dots + s_{increase}(x_k)$$

$$\ln\left(\frac{\hat{\pi}_{decrease}}{\hat{\pi}_{no\ change}}\right) = \beta_{0(decrease)} + s_{decrease}(x_1) + \dots + s_{decrease}(x_k).$$

Under the GLM, coefficients are interpreted additively when using the normal distribution, while under the multinomial distribution, odds ratios are interpreted multiplicatively. GAMs, however, do not produce directly interpretable coefficients. Instead, the effective degrees of freedom (edf) of each smoothing function are reported as an indicator of relationship complexity. An edf of 1 indicates a linear relationship, while an edf greater than 1 indicates nonlinearity (Wood, 2017). As the edf increases, the smoothing function becomes increasingly flexible, reflecting greater complexity in the relationship between the predictor and the response.

To examine model fit, adjusted R^2 and Akaike's Information Criterion (AIC) were computed for each model and compared. When modeling wind reduction using a normal distribution, the traditional adjusted R^2 was examined, however, this fit index cannot be computed for multinomial models. Thus, when modeling wrack deposition using the multinomial distribution, McFadden's pseudo- R^2 was examined (McFadden, 1987). While the traditional R^2 represents the proportion of variability explained by the model, McFadden's pseudo- R^2 can be interpreted as the proportion of total deviance accounted for by the model. To formally compare the GLM and GAM within each outcome, likelihood ratio tests (LRTs) were conducted, where a significant result indicates that the additional flexibility of the GAM provides a statistically better fit to the data than the GLM.

Model results were visualized using two approaches. First, predicted outcomes were plotted as a function of wind speed with wind angle held constant at 121, allowing for direct comparison of the GLM and GAM across the range of observed wind speeds. Second, heatmaps were generated across the full range of observed wind speed and wind angle values, enabling visualization of the influence of wind conditions on predicted outcomes.

All statistical analyses and data visualization were conducted in R (version 4.6.0) (R Core Team, 2026). All GAMs were fit using the *mgcv* package while multinomial logistic regression GLMs were fit using the *nnet* package (Venables and Ripley, 2002; Wood, 2011; Wood, 2017). Data management was performed using the *tidyverse* and *broom* packages, with figures produced using the *ggplot2*, *patchwork*, and *metR* packages (Wickham et al., 2019; Campitelli, 2021; Pederson, 2025; Robinson et al, 2026). Statistical significance was defined *a priori* as $p < 0.05$. All data and code can be found on the corresponding GitHub repository, <https://github.com/CGMlabUWF/beachwrack-aeolian-research-2026>.

Results

Wind Reduction

Table 1 presents modeling results for wind reduction. Both wind speed and wind angle were significant predictors of wind reduction under both modeling frameworks ($p < 0.001$). Under the GLM, wind angle ($\hat{\beta} = 0.20$, 95% CI [0.18, 0.22]) and wind speed ($\hat{\beta} = 7.00$, 95% CI [6.85, 7.15]) were positively associated with wind reduction. Under the GAM, both predictors exhibited strongly nonlinear relationships with wind reduction, as indicated by effective degrees of freedom substantially greater than one (wind angle edf = 5.40; wind speed edf = 7.87). The GAM explained slightly more variance than the GLM ($R^2 = 0.276$ versus 0.261) and produced a

lower AIC (209,136.0 versus 209,748.7). A likelihood ratio test confirmed that the GAM provided a significantly better fit to the data ($\chi^2 = 636.88$, $p < 0.001$).

Figure 2 illustrates contrasting representations of the relationship between wind speed and wind reduction. The GLM assumes that wind reduction increases at a constant rate across the observed wind-speed gradient. In contrast, the GAM identified multiple response regions characterized by differing rates of change in wind reduction. Wind reduction increased rapidly at lower wind speeds, stabilized across intermediate wind speeds, and increased again at higher wind speeds before approaching a plateau. These results indicate that the relationship between wind speed and flow reduction varies across the observed environmental gradient rather than following a single linear trend. Predictions at wind speeds below approximately 2.5 m/s and above 5.5 m/s should be interpreted cautiously due to limited observations within these portions of the dataset.

Figure 3 demonstrates predicted wind reduction across combinations of wind speed and wind angle. Both models predict increasing wind reduction with increasing wind speed and wind angle; however, the GAM produces a nonlinear response surface that differs from the more uniform gradient predicted by the GLM. Contour lines indicate that wind reduction increased primarily along the wind-speed gradient, with values ranging from approximately 20% at low wind speeds to over 60% under the highest wind-speed and wind-angle combinations. Wind speed emerged as the dominant control on wind reduction, while wind angle modified the magnitude of the response. The GAM results further indicate that the influence of wind speed varies across environmental space, suggesting that airflow modification by wrack changes under different wind regimes.

Differences between the GLM and GAM prediction surfaces are shown in Figure 4. Across much of the environmental space, differences between models were relatively modest, typically less than 4% wind reduction. However, localized regions exhibited substantially larger departures. The GAM predicted greater wind reduction than the GLM under higher wind-angle conditions, with differences exceeding 8–10% near the upper portion of the observed angle gradient. Conversely, the GAM predicted lower wind reduction than the GLM at the lowest and highest wind-speed ranges, where differences approached 4–6%. These results indicate that the nonlinear model redistributed predicted wind reduction across environmental space rather than uniformly increasing or decreasing predictions. The largest departures occurred in regions where wind angle exerted a stronger influence on the response surface, suggesting that angle-dependent effects become increasingly important under specific wind regimes.

Overall, both wind speed and wind angle emerged as important controls on wind reduction. While the GLM captured the general positive relationships between these variables and flow reduction, the GAM revealed that the magnitude of those relationships varies across the environmental gradient. Although the overall improvement in model fit was modest, the nonlinear model identified localized regions of enhanced and reduced wind reduction that were not captured by the linear model, indicating condition-dependent responses in wrack-mediated airflow modification.

Sediment Deposition

Table 2 presents modeling results for wrack deposition. Under the GLM framework, wind angle was negatively associated with both the probability of sediment accumulation (OR = 0.97, 95% CI [0.96, 0.98], $p < 0.001$) and sediment loss (OR = 0.99, 95% CI [0.98, 0.99], $p < 0.001$)

relative to no change. Wind speed was positively associated with the probability of sediment accumulation (OR = 1.12, 95% CI [1.08, 1.18], $p < 0.001$) but was not significantly related to sediment loss ($p = 0.70$). In contrast, the GAM identified significant nonlinear relationships between both environmental variables and deposition outcomes. Effective degrees of freedom ranged from 4.34 to 8.70, indicating substantial departures from linearity across all predictor-response combinations.

The GAM provided a substantially better fit than the GLM, explaining more deviance ($R^2 = 0.009$ versus 0.002) and yielding a considerably lower AIC (47,368.01 versus 64,280.66). A likelihood ratio test confirmed that the GAM significantly outperformed the GLM ($\chi^2 = 16,960.66$, $p < 0.001$). Despite this improvement, both models explained only a small proportion of the overall variation in deposition outcomes, indicating that factors beyond wind speed and wind angle account for much of the observed variability.

Figure 5 illustrates fundamental differences in predicted deposition responses across the wind-speed gradient. The GLM predicts monotonic changes in probability, implying that sediment accumulation and sediment loss vary at a constant rate with increasing wind speed. In contrast, the GAM identifies multiple peaks and troughs across the observed wind-speed range, indicating that deposition responses vary across environmental conditions rather than following a single directional trend. This pattern is particularly evident for sediment loss, where the GLM indicates little change in probability across the wind-speed gradient while the GAM reveals pronounced fluctuations, including localized increases and decreases in erosion probability. These results suggest that wind-speed effects on deposition are condition-dependent and are not adequately characterized by simple linear relationships.

These differences become more apparent in Figure 6. The GLM produced relatively uniform probability surfaces characterized by smooth gradients across environmental space. In contrast, the GAM identified distinct regions of elevated and reduced probabilities for both sediment accumulation (P(Increase)) and sediment loss (P(Decrease)). Areas of elevated sediment accumulation occurred within specific combinations of wind speed and wind angle rather than across the entire environmental gradient. Similarly, regions of elevated sediment loss occupied different portions of environmental space and exhibited localized probability maxima that were not apparent in the GLM predictions. The spatial separation of accumulation and erosion probabilities indicates that sediment responses vary according to specific combinations of environmental conditions rather than changing uniformly across the wind regime. These results suggest that both sediment retention and sediment loss are governed by nonlinear relationships among wind speed and wind angle, with localized environmental conditions exerting a stronger influence on predicted outcomes than implied by the linear model.

Differences between the GLM and GAM depositional probability surfaces are shown in Figure 7. For sediment accumulation (P(Increase)), differences between modeling approaches were generally modest, with most of the environmental space exhibiting probability differences of less than 0.2. The GAM typically predicted lower probabilities of accumulation than the GLM across moderate wind speeds (3.5-5.0 m/s) and intermediate wind angles (115-130°), while localized regions of higher accumulation probability occurred near the upper wind-speed range. In contrast, larger differences were observed for sediment loss (P(Decrease)). Across much of the environmental gradients, the GAM predicted lower probabilities of sediment loss than the GLM; however, substantial localized departures occurred near the lower and upper limits of the wind-speed gradient, where probability differences exceeded 0.3. These patterns indicate that

nonlinear responses were more strongly expressed for erosion-related outcomes than for sediment accumulation and suggest that sediment loss is particularly sensitive to specific combinations of wind speed and wind angle.

Most notably, the GLM identified no significant relationship between wind speed and sediment loss ($p = 0.700$), whereas the GAM revealed a significant nonlinear relationship (edf = 4.34, $p < 0.001$). This divergence suggests that important depositional dynamics are obscured under linear assumptions and that environmental drivers influence sediment responses differently across the observed aerodynamic gradients. Although wind speed and wind angle explained only a small proportion of the overall variation in deposition outcomes, the GAM consistently identified nonlinear relationships that were not captured by the GLM, indicating that sediment accumulation and erosion are governed by condition-dependent responses rather than simple linear trends.

Discussion

Wrack as a Dynamic Aerodynamic Roughness Element

The results demonstrate that wrack functions as an effective aerodynamic roughness element capable of substantially modifying near-surface airflow. Both wind speed and wind angle significantly influenced flow reduction, indicating that wrack interacts dynamically with prevailing environmental conditions. Similar to dune vegetation and other roughness elements such as woody debris and sand fences (Hotta et al., 1987; Eamer and Walker, 2010; Heathfield and Walker, 2011; Itzkin et al., 2019), our results demonstrate that wrack functions as an aerodynamic roughness element capable of modifying near-surface airflow and influencing sediment deposition dynamics. The observed relationship between wind conditions and flow

reduction is consistent with established theories of aeolian transport, which demonstrate that roughness elements alter boundary-layer flow and reduce the shear stress available for sediment entrainment and transport (Raupach, 1992; Okin, 2008).

Wind speed alone explained approximately 25% of the variation in flow reduction, indicating that much of the observed variability remained unexplained. This level of explanatory power is not unexpected in aeolian field environments, where process-response relationships are influenced by turbulent airflow, surface heterogeneity, obstacle geometry, sediment characteristics, and short-term fluctuations in atmospheric conditions (Davidson-Arnott et al., 2005; Ellis et al., 2012; Sherman et al., 2012; Poortinga et al., 2016; Martin et al., 2016; Van Rijn, 2018). Rather than reflecting weak process controls, this unexplained variation highlights the inherent complexity of natural sediment transport systems and suggests that wrack-mediated airflow modification is governed by multiple interacting processes operating across environmental gradients.

This complexity becomes more apparent when comparing the GLM and GAM results. The GLM assumes that wind reduction increases at a constant rate across the observed wind-speed gradient, whereas the GAM indicates that wrack does not function as a constant windbreak. Instead, its effectiveness varies across environmental conditions. Wind reduction increased rapidly at lower wind speeds, stabilized across intermediate wind speeds, and increased again at higher wind speeds before approaching a plateau. These multiple response regions suggest that airflow modification by wrack is governed by nonlinear aerodynamic processes rather than simple linear scaling relationships.

One possible explanation for this pattern is that the interaction between airflow and wrack changes across the observed wind-speed gradient. At lower wind speeds, relatively small

increases in wind energy may substantially increase drag and wake formation around individual wrack elements, producing rapid increases in sheltering effectiveness. At intermediate wind speeds, airflow may become increasingly adjusted to the obstacle, resulting in a temporary stabilization of sheltering effects. At higher wind speeds, enhanced wake development and flow adjustment around the wrack accumulation may further increase flow reduction before approaching a practical upper limit where additional wind energy produces diminishing changes in sheltering effectiveness. Although direct measurements of turbulence were not collected in this study, such interpretations are consistent with observations of airflow modification around vegetation canopies and other roughness elements that alter near-surface wind flow (Lancaster and Baas, 1998; Eamer and Walker, 2010).

Wind angle further reinforces the interpretation that wrack functions as a dynamic aerodynamic roughness element. While wind speed governs the amount of energy available within the system, wind angle influences how that energy interacts with the wrack accumulation. The GAM results indicate that wind reduction varied across combinations of wind speed and wind angle, suggesting that wrack effectiveness is partly dependent upon its orientation relative to incident airflow.

This finding is consistent with studies of vegetation and other porous roughness elements, where the aerodynamic response of the obstacle is strongly influenced by flow direction (Lancaster and Baas, 1998). Changes in wind angle alter the effective frontal area exposed to airflow and influence the degree to which air is forced through, around, or over the roughness element. Consequently, two wind events with similar velocities may produce substantially different aerodynamic and geomorphic outcomes depending on their orientation relative to wrack accumulations. The nonlinear response identified by the GAM suggests that these directional

effects are not constant across the observed range of wind angles. Instead, certain wind orientations appear to promote disproportionately greater reductions in airflow than would be expected under a simple linear relationship.

From a geomorphic perspective, this distinction is important because wind direction is typically evaluated as a control on transport pathways and net sediment movement, whereas less attention has been given to how directional variability influences the aerodynamic effectiveness of natural roughness elements (Ellis and Sherman, 2013; Walker et al., 2017). The results presented here suggest that directional controls may strongly influence the effectiveness of natural roughness elements and therefore the locations where sediment transport pathways are interrupted.

Previous research has largely focused on vegetation as the primary biological roughness element responsible for modifying airflow and facilitating dune development. In contrast, wrack has received comparatively little attention despite its widespread occurrence on sandy coastlines and frequent accumulation following storm events. The present results indicate that wrack can generate measurable aerodynamic effects similar to those commonly attributed to vegetation by creating localized zones of aerodynamic sheltering (Nordstrom et al., 2011a; Nordstrom et al., 2012; Tereszkievicz and Ellis, 2025). The nonlinear responses identified here further suggest that wrack behaves as a dynamic roughness element whose influence varies across environmental conditions rather than as a passive obstacle producing a uniform reduction in wind velocity.

The nonlinear response surfaces identified here suggest that wrack should not be viewed as a passive obstacle producing a uniform reduction in wind velocity. Rather, it functions as a condition-dependent roughness element whose influence emerges from the interaction among

wind speed, wind direction, and obstacle structure. This interaction likely explains much of the nonlinear behavior observed in the response surfaces and provides a mechanistic basis for understanding why wrack effectiveness varies across environmental conditions. Consequently, wrack should be viewed as a dynamic component of the coastal sediment transport system rather than a static barrier. Similar to vegetation and other natural roughness elements, its influence on sediment transport arises through complex interactions among airflow modification, aerodynamic sheltering, and wake development (Baas, 2002). The results therefore suggest that wrack occupies a functional role within coastal dune systems that extends beyond simply obstructing wind flow, instead acting as a dynamic geomorphic agent whose effectiveness varies across environmental conditions.

Wrack as a Conditional Sediment-Trapping Feature

The deposition results reveal a substantially more complex response than that observed for airflow modification. Although wind speed and wind angle were statistically significant predictors of deposition dynamics, they explained only a small proportion of the overall variation. This outcome highlights the inherently multivariate nature of sediment deposition, which is influenced by sediment availability, moisture conditions, grain-size distributions, antecedent surface conditions, beach topography, and short-term meteorological variability (Davidson-Arnott et al., 2005; Barrineau and Ellis, 2013; Schmutz et al., 2025). Despite the low explanatory power of the models, the response surfaces generated by the GAM provide important insight into the sediment trapping capacity of wrack. Rather than exhibiting uniform responses across the wind regime, deposition probabilities varied according to specific combinations of wind speed and wind angle. Areas of elevated deposition probability occupied

discrete portions of environmental space, while regions of elevated erosion probability occurred elsewhere. These patterns suggest that the sediment-trapping effectiveness of wrack is conditional upon environmental conditions rather than constant across all wind regimes.

The distinction between airflow modification and sediment deposition is particularly important. The wind reduction models demonstrated relatively consistent sheltering effects across much of the observed environmental gradient, whereas depositional responses were considerably more variable. This suggests that the creation of aerodynamic shelter alone is insufficient to guarantee deposition, as depositional outcomes depend on the interaction between reductions in transport capacity and sediment availability (Okin, 2008). Even highly effective aerodynamic barriers may fail to produce measurable deposition when sediment availability is limited, while relatively modest reductions in wind velocity may generate substantial deposition when transport rates are high. This interpretation is consistent with broader aeolian theory, which emphasizes that both transport capacity and sediment availability govern depositional outcomes (Baas, 2007; Ellis and Sherman, 2013).

The results also reinforce the complementary roles of wind speed and wind direction in sediment transport systems. Wind speed governs transport potential by determining whether sufficient energy exists to entrain and move sediment, while wind direction influences transport pathways and patterns of sediment redistribution (Lancaster and Baas, 1998; Ellis and Sherman, 2013). However, increasing transport potential alone does not guarantee enhanced deposition around wrack. The GAM results indicate that deposition occurs most readily under particular combinations of wind speed and wind angle, suggesting that favorable aerodynamic conditions are required for sediment trapping to occur. Consequently, wind speed may determine how much

sediment is available for transport, whereas wind direction influences where and under what conditions that sediment is retained.

These findings suggest that wrack may function similarly to vegetation during the earliest stages of dune development. Numerous studies have demonstrated that vegetation traps sediment by creating localized zones of reduced flow velocity that facilitate positive feedbacks between sediment accumulation and vegetation growth (Hesp, 1989; Durán Vinent and Moore, 2015; Durán Vinent et al., 2021). Wrack may provide a comparable function by acting as a temporary roughness element that initiates sediment accumulation prior to vegetation establishment (Tereszkiewicz and Ellis, 2025). Through repeated episodes of sediment trapping, wrack accumulations may contribute to embryo dune formation, increase local surface roughness, and create favorable conditions for subsequent colonization by dune-building vegetation. In this manner, wrack may serve as an important intermediary between short-term sediment transport processes and longer-term dune development, consistent with previous studies that identify wrack as a linkage between physical and ecological processes within beach-dune systems (Nordstrom et al., 2012; Hyndes et al., 2022; Tereszkievicz and Ellis, 2025).

Beyond localized sediment trapping, these findings suggest that wrack may contribute to the natural geomorphic processes that underpin coastal resilience. Coastal dunes develop through the cumulative effects of repeated depositional events, many of which are initiated by relatively small roughness elements that disrupt airflow and create localized zones of sediment accumulation (Hesp, 2002). By modifying near-surface wind flow and promoting sediment retention under favorable environmental conditions, wrack may contribute to the earliest stages of dune recovery following storms and other disturbance events. These initial accumulations can create microtopographic irregularities that enhance subsequent sediment trapping and potentially

facilitate vegetation establishment, reinforcing positive feedbacks that promote dune growth and stabilization (Corenblit et al., 2011; Durán Vinent et al., 2021; Rinaldo et al., 2021).

The ecological and geomorphic functions of wrack are particularly relevant given the increasing emphasis on nature-based solutions for coastal management. Whereas traditional engineering approaches often seek to stabilize shorelines through structural interventions, natural materials such as wrack operate by enhancing existing sediment transport processes and supporting the organization of coastal landforms (Temmerman et al., 2013; Farrell et al., 2023). Although wrack alone is unlikely to drive large-scale dune development, its influence on airflow and sediment retention suggests that it may serve as an important component of the broader suite of processes contributing to dune recovery, coastal resilience, and long-term landscape adaptation.

From a management perspective, these findings support growing recognition of beach wrack as a nature-based component of coastal resilience (Robbe et al., 2021, Joyce et al, 2022). Wrack is frequently removed from recreational beaches for aesthetic purposes, yet such practices simultaneously remove a naturally occurring roughness element capable of modifying airflow and promoting sediment retention (Nordstrom et al., 2007; Williams and Feagin, 2010; Nordstrom et al., 2012; Sigren et al., 2014). The results presented here suggest that wrack does not function as a uniformly effective sediment trap; however, under appropriate environmental conditions it can contribute to localized sediment accumulation, early-stage dune development, and post-disturbance recovery. Consequently, routine wrack removal may reduce opportunities for natural sediment retention and dune recovery, particularly following disturbance events when natural roughness elements are limited. Viewed within this broader geomorphic context, wrack represents more than simply organic material deposited on the beach surface; it functions as a

dynamic component of coastal dune systems that can influence sediment pathways, landform development, and the resilience of coastal landscapes.

The Importance of Nonlinear Approaches for Aeolian Research

One of the most important findings of this study is that nonlinear modeling approaches reveal process dynamics that remain obscured under traditional linear frameworks. The significance of the GAM results lies not simply in improved statistical performance, but in what they reveal about system behavior.

The GLM assumes that environmental responses occur at constant rates across predictor gradients. Under this framework, wrack effectiveness increases uniformly with increasing wind speed, and deposition responses change monotonically across environmental space. The GAM reveals a fundamentally different interpretation. Both airflow and deposition responses varied across environmental gradients, producing multiple regions of enhanced and reduced effectiveness. These results suggest that wrack-mediated processes do not operate through simple linear relationships, but rather emerge from interactions among wind conditions, obstacle characteristics, and sediment transport processes.

These findings are consistent with the threshold-dependent nature of aeolian systems. Sediment entrainment, transport, deposition, vegetation-mediated trapping, and dune development all exhibit nonlinear responses to environmental forcing (Baas, 2002, Baas 2007). Small changes in environmental conditions can produce disproportionately large changes in sediment transport behavior when critical thresholds are exceeded, while similar changes may have little effect under other conditions. The elevated effective degrees of freedom (edf) observed throughout the GAM analyses suggest that wrack-mediated airflow and sediment retention operate through similar nonlinear mechanisms. Rather than responding uniformly to

increasing wind speeds or changing wind directions, wrack effectiveness appears to vary across environmental gradients, producing distinct regions of enhanced and diminished aerodynamic and depositional influence.

The deposition results provide the clearest example of the value of nonlinear approaches. The GLM suggested that wind speed was unrelated to deposition decreases, whereas the GAM revealed a significant nonlinear relationship. Consequently, the GAM did not merely improve model fit; it altered interpretation of the system by demonstrating that depositional responses vary across environmental space rather than following a single directional trend. Similar patterns have been identified in other aeolian environments where interactions among airflow, surface roughness, vegetation structure, and sediment availability generate complex responses that are poorly represented by linear models (Baas, 2007).

More broadly, these findings highlight the importance of applying nonlinear analytical approaches to studies of coastal dune recovery and sediment transport. Coastal dune systems are governed by numerous interacting biophysical processes operating across multiple spatial and temporal scales, including airflow modification, sediment transport, vegetation establishment, and feedbacks between ecological and geomorphic processes (Corenblit et al., 2011; Durán Vinent and Moore, 2015; Durán Vinent et al., 2021). Because these processes frequently involve thresholds, feedbacks, and emergent behavior, linear approaches may oversimplify the mechanisms governing landscape change.

Collectively, these findings suggest that wrack functions as a dynamic, condition-dependent geomorphic agent whose aerodynamic and depositional influences vary across the wind regime. More broadly, they demonstrate the value of nonlinear analytical approaches for identifying threshold behavior, revealing hidden process interactions, and improving

understanding of aeolian processes operating across complex environmental gradients. Such approaches may prove particularly valuable for evaluating the role of natural roughness elements in coastal resilience and dune recovery, where system responses are often governed by interactions among multiple environmental controls rather than by single dominant drivers.

Conclusions

This study demonstrates that beach wrack functions as an effective aerodynamic roughness element capable of modifying near-surface airflow and influencing localized sediment deposition. Wrack consistently reduced wind velocities across the study site, supporting its role as a natural flow-disrupting feature within coastal sediment transport systems. However, the results indicate that wrack does not function as a uniform windbreak or sediment trap. Instead, its effectiveness varies across combinations of wind speed and wind angle, producing condition-dependent responses in both airflow modification and sediment deposition.

The wind reduction analyses revealed that wrack-mediated sheltering is governed by nonlinear aerodynamic processes rather than simple linear relationships. Wind speed and wind angle both significantly influenced flow reduction, and the GAM identified multiple response regions that were not captured by the GLM. Similarly, sediment deposition exhibited distinct zones of elevated and reduced deposition probability across environmental space, suggesting that the geomorphic influence of wrack varies according to prevailing wind conditions. These findings indicate that wrack functions as a dynamic geomorphic agent whose influence emerges through complex interactions among airflow modification, turbulence generation, sediment availability, and environmental forcing.

More broadly, this study highlights the value of nonlinear analytical approaches for aeolian research. Although the GAM produced only modest improvements in overall explanatory power for some analyses, it fundamentally altered interpretation of the system by revealing threshold-like responses, changing process states, and environmental conditions under which wrack effectiveness increased or decreased. These findings demonstrate that important aeolian dynamics may remain obscured under traditional linear frameworks and emphasize the importance of flexible modeling approaches for understanding complex sediment transport systems.

From a management perspective, the results support growing recognition of beach wrack as a nature-based component of coastal resilience. While wrack is frequently removed from recreational beaches for aesthetic reasons, its ability to modify airflow and promote localized sediment retention suggests that it may contribute to early-stage dune development and post-disturbance recovery. Rather than being viewed solely as beach debris, wrack should be considered a functional component of coastal dune systems that can influence sediment transport and landscape evolution. Future research should evaluate how wrack characteristics, sediment supply, moisture conditions, and longer-term environmental variability influence these interactions across broader spatial and temporal scales.

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Tables and Figures

Table 1 - Results of generalized linear models (GLM) and generalized additive models (GAM) examining relationships between wind speed, wind angle, and wind reduction. GLM results are reported as parameter estimates ($\hat{\beta}$) with 95% confidence intervals, while GAM results are presented as effective degrees of freedom (edf) and associated significance values. Model performance is summarized using R^2 and Akaike Information Criterion (AIC).

Predictor	GLM	GAM
	Estimate (95% CI) p-value	edf p-value
Wind Angle	0.20 (0.18, 0.22) < 0.001	5.40 < 0.001
Wind Speed	7.00 (6.85, 7.15) < 0.001	7.87 < 0.001
R^2	0.261	0.276
AIC	209748.7	209136.0

Table 2 - Results of generalized linear models (GLM) and generalized additive models (GAM) examining relationships between wind angle, wind speed, and sediment accumulation (Increase) and sediment loss (Decrease) relative to no change. GLM results are presented as odds ratios (OR) with 95% confidence intervals, while GAM results are reported as effective degrees of freedom (edf) and associated significance values. Model fit statistics include pseudo- R^2 and Akaike Information Criterion (AIC).

Predictor	Increase		Decrease	
	GLM OR (95% CI) p-value	GAM edf p-value	GLM OR (95% CI) p-value	GAM edf p-value
Wind Angle	0.97 (0.96, 0.98) < 0.001	8.70 < 0.001	0.99 (0.98, 0.99) < 0.001	6.11 < 0.001
Wind Speed	1.12 (1.08, 1.18) < 0.001	6.02 < 0.001	0.99 (0.95, 1.04) 0.700	4.34 < 0.001
R^2	0.002	0.009	0.002	0.009
AIC	64280.66	47368.01	64280.66	47368.01



Figure 1 – Picture of field experiment setup showing 2D anemometers upwind and downwind of wrack pile along with single-point LiDAR.

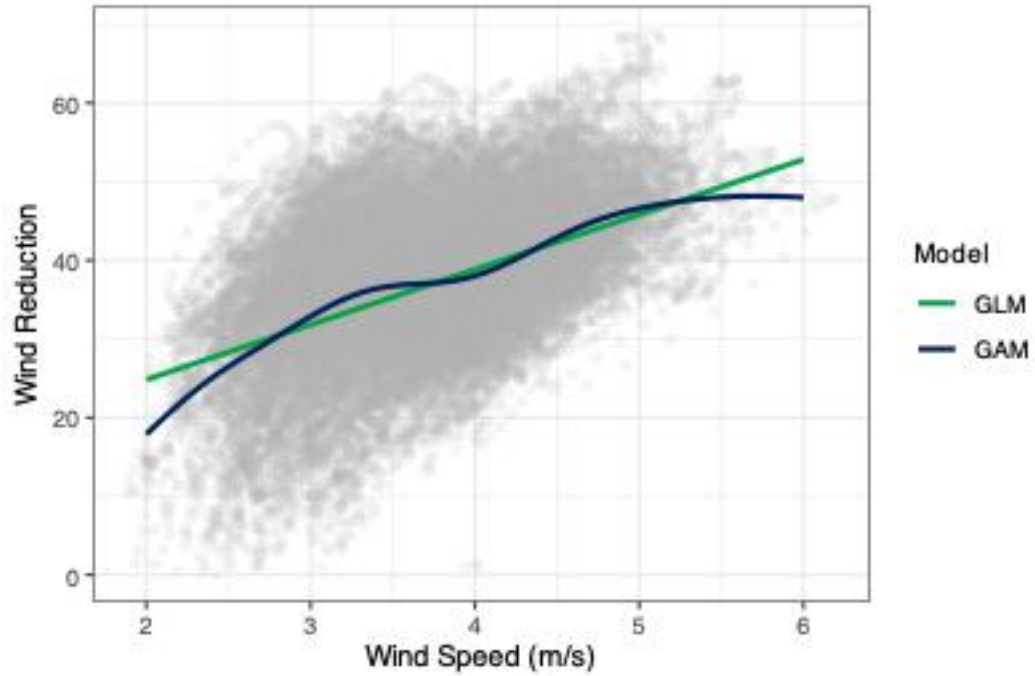


Figure 2 - Predicted wind reduction across the observed wind-speed gradient for generalized linear models (GLM) and generalized additive models (GAM). Gray points represent observed wind-reduction measurements.

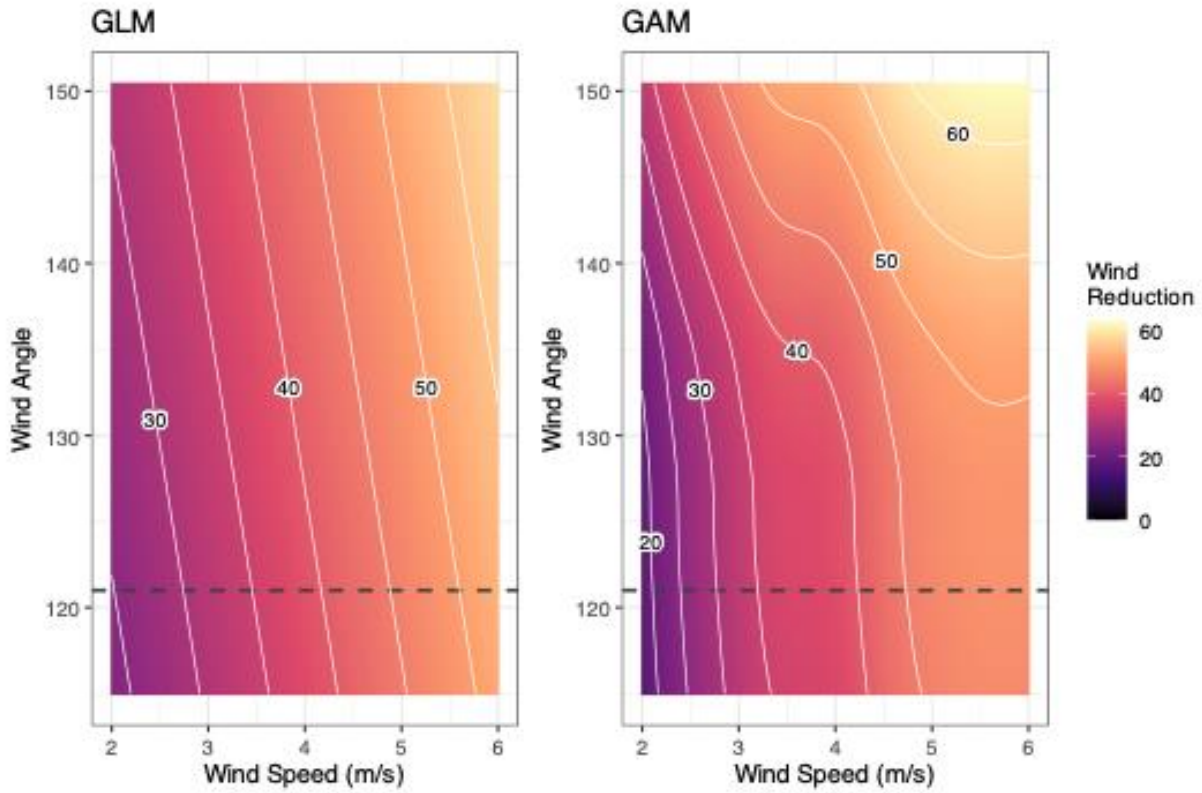


Figure 3 - Predicted wind-reduction surfaces as a function of wind speed and wind angle for generalized linear models (GLM) and generalized additive models (GAM). Contour lines represent equal levels of predicted wind reduction. Dashed line indicates azimuth of the instrument array at 121°.

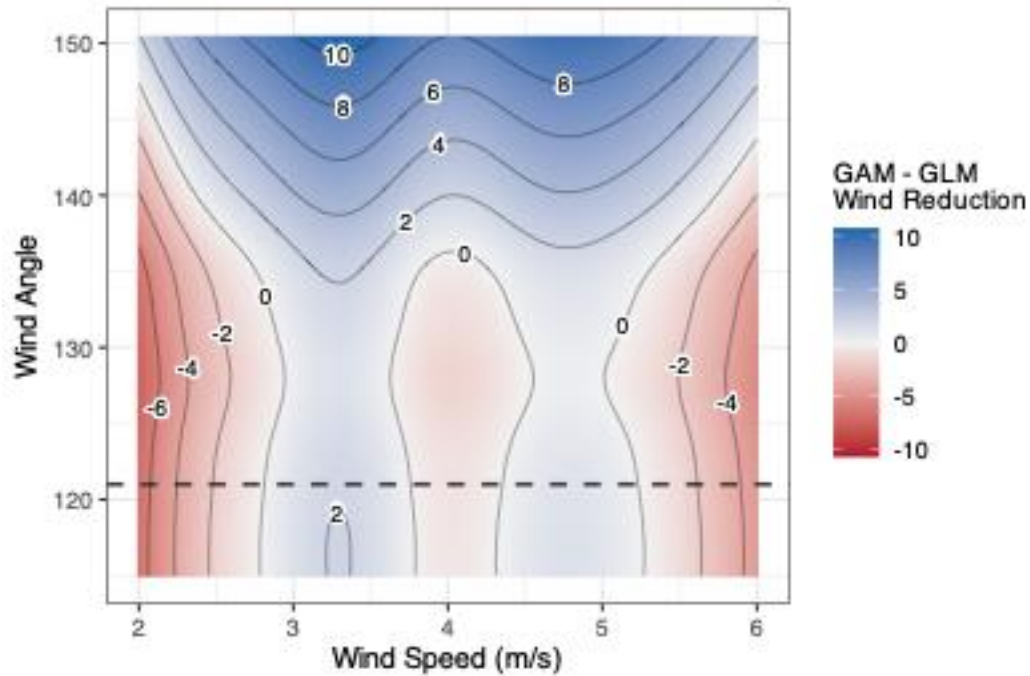


Figure 4 - Difference surface illustrating GAM – GLM predicted wind reduction. Positive values indicate regions where the GAM predicts greater wind reduction than the GLM, whereas negative values indicate regions where the GAM predicts lower wind reduction. Contours represent differences in predicted wind reduction (%). Dashed line indicates azimuth of the instrument array at 121°.

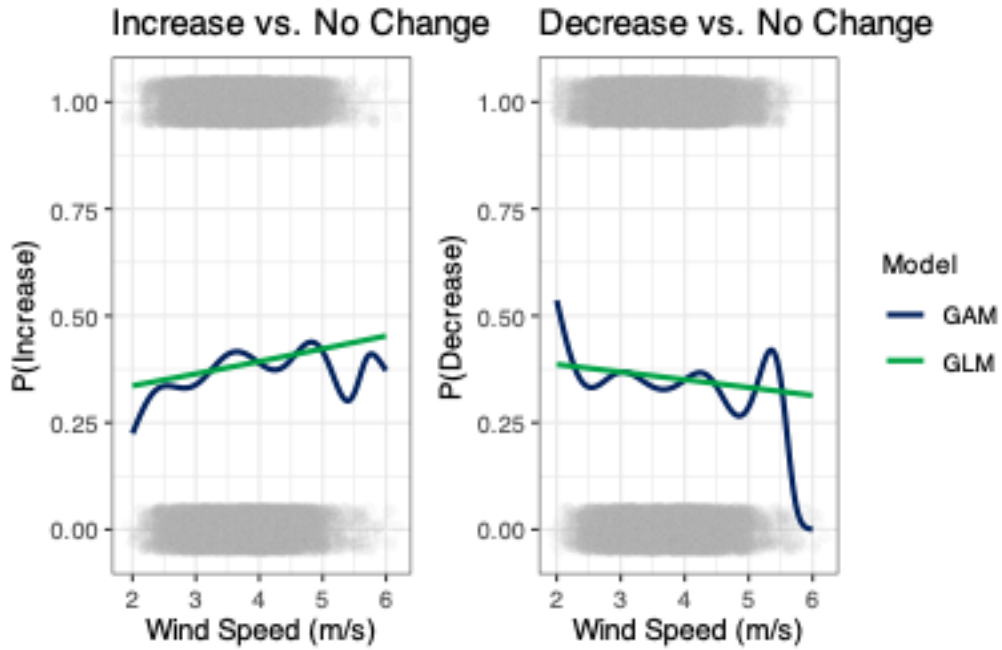


Figure 5 - Predicted probabilities of sediment accumulation (Increase) and sediment loss (Decrease) across the observed wind-speed gradient for generalized linear models (GLM) and generalized additive models (GAM). Gray points represent observed binary outcomes.

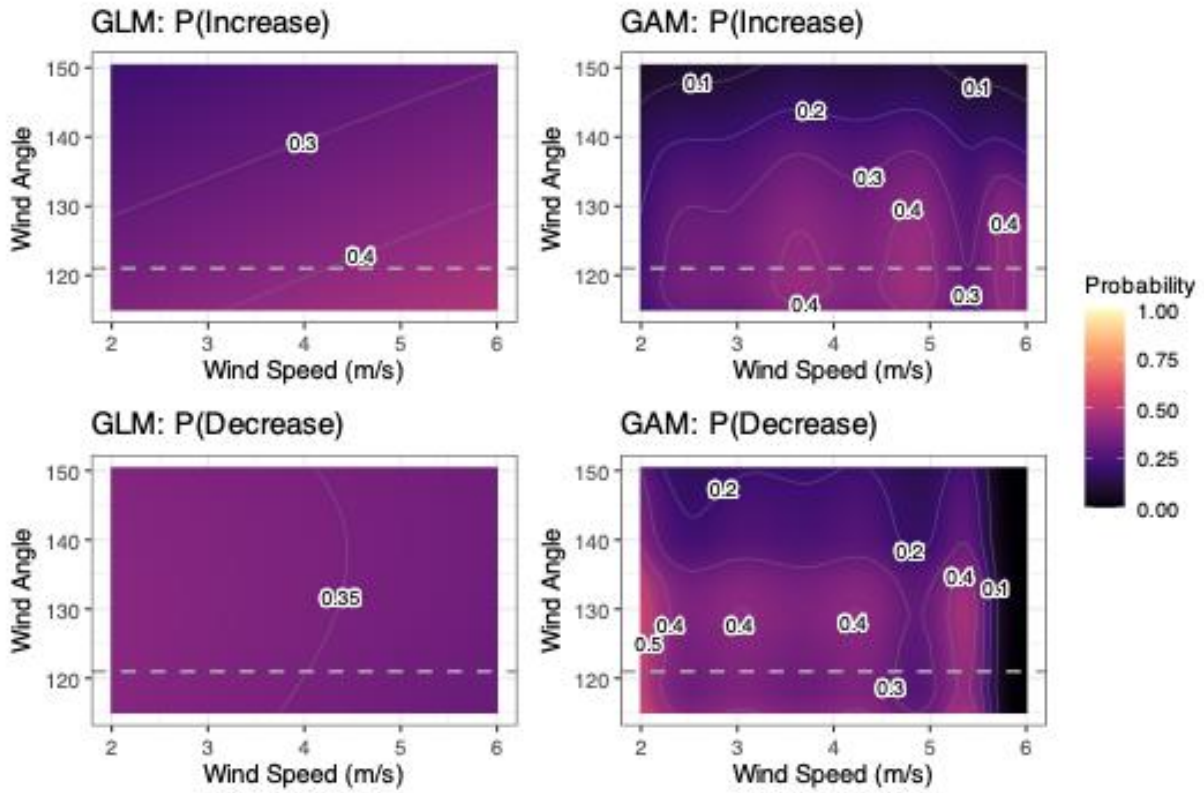


Figure 6 - Predicted probability surfaces for sediment accumulation (P(Increase)) and sediment loss (P(Decrease)) as a function of wind speed and wind angle. Dashed line indicates azimuth of the instrument array at 121°.

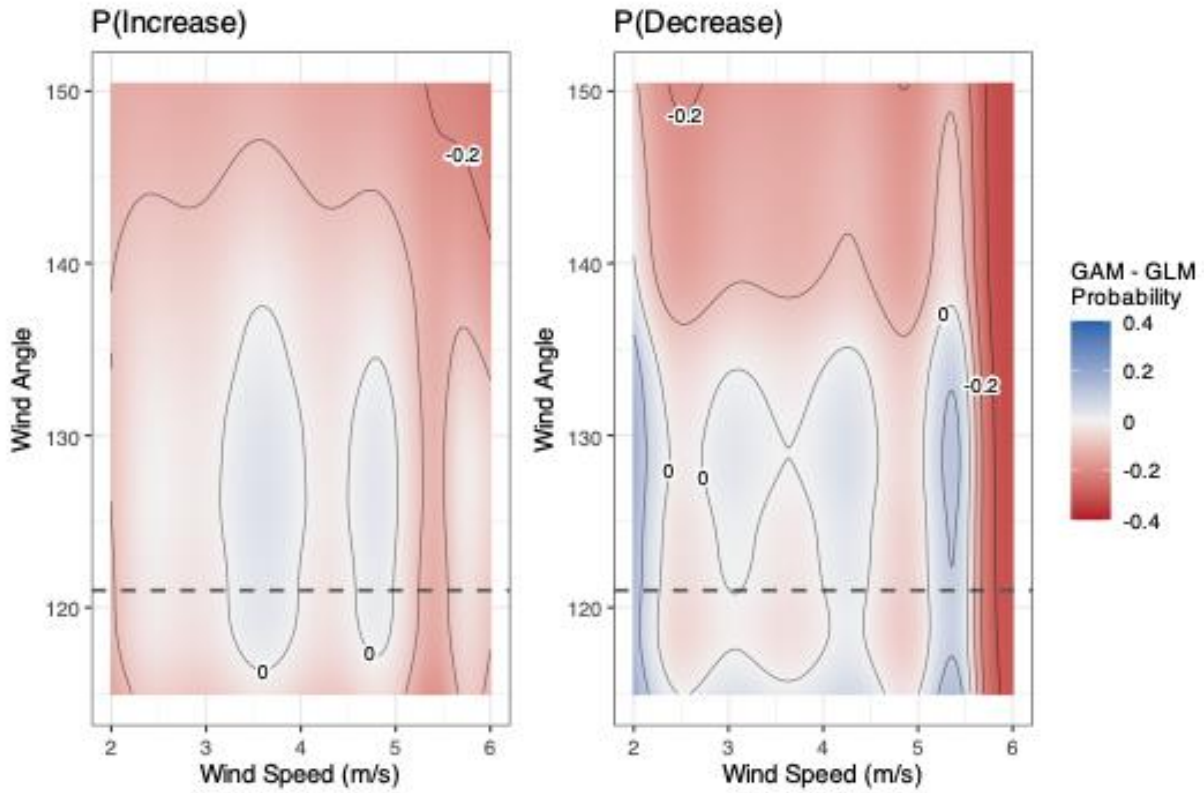


Figure 7 - Difference surfaces illustrating GAM – GLM predicted probabilities for sediment accumulation (P(Increase)) and sediment loss (P(Decrease)). Contour lines represent equal levels of differences in sediment accumulation probability. Dashed line indicates azimuth of the instrument array at 121°.