

Agency Through Design: Behavior-Specific Use Patterns of Horses Across Four Different Turnout Areas in the Netherlands

Inga Wolframm^{1,2,*}, Kerstin Vogel², Yteke Elte², Mattias Lindström³, Karl Forssman³, and Thomas Engels¹

¹Applied Research Centre, Van Hall Larenstein University of Applied Sciences, 6882 CT Velp, the Netherlands

²Department of Clinical Sciences, Faculty of Veterinary Medicine, Utrecht University, Utrecht, the Netherlands

³Hoofstep, Inc. HQ, P.O. Box 1334, Wrightwood, CA 92397, United States

*Author to whom any correspondence should be addressed; Email: inga.wolframm@hvhl.nl

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Abstract

Equine turnout areas are commonly designed to maximize open space. However, research in more naturalistic settings suggests that horses use landscape features selectively. This study examined how horses' spatial use patterns vary across turnout designs with different levels of structural complexity, and whether the use of specific features differs according to behavioral state and time of day. Horses ($N = 26$) at four Dutch yards (A–D; size range: 6,477 m²–37,489 m²) differing in landscape design were monitored for 10 consecutive days using Hoofstep® GPS–IMU sensors. Behavior was automatically classified into four categories (Eating, Resting, Active, Highly Active). Spatial preprocessing was conducted in Python, with ArcGIS used for cartographic checking, yielding a final dataset of 3,856.50 monitoring hours. Feature selection relative to availability was quantified using Manly's Selection Ratios (MSR). Log-transformed MSR values were analyzed using yard-specific linear mixed models. Landscape features significantly influenced spatial selection across all yards (A: $F(12,940) = 98.199$, $P < 0.001$; B: $F(7,1460) = 124.663$, $P < 0.001$; C: $F(4,273) = 19.326$, $P < 0.001$; D: $F(6,498) = 38.691$, $P < 0.001$). Behavior $\times$ landscape feature interactions were also significant in all models (all $P < 0.001$), indicating behavior-specific spatial selection. Significant interactions involving time of day were observed primarily in the more structurally heterogeneous environments. Findings indicate that behavior-specific spatial organization was fundamentally shaped by structural environment. Landscape heterogeneity therefore appears to support behavioral agency by providing horses with functionally distinct spatial options. These findings support landscape design as an important consideration for equine welfare, with potential co-benefits for biodiversity.

Keywords

Equine welfare; spatial behavior; landscape heterogeneity; environmental enrichment; behavioral agency; sensor technology

1. Introduction

In densely populated regions such as the Netherlands, horses are kept in spatially constrained environments as a matter of necessity. Land availability is limited, turnout areas are small, and the management systems within which horses are housed reflect the competing pressures of agricultural land use, urban proximity, and regulatory oversight [1,2]. Within these constraints, outdoor access has increasingly been recognized as a welfare requirement, and providing

horses with turnout time has become standard practice across much of Europe [3–5]. Yet outdoor access alone is not equivalent to behavioral opportunity. A horse in a bare paddock may have the opportunity to move, but that environment offers little motivation for movement. The result is a welfare standard defined primarily by the absence of confinement rather than by the presence of meaningful choice.

This distinction has become increasingly central to animal welfare science. The Five Domains model explicitly identifies

positive mental experience as a welfare domain in its own right, moving beyond the deficit-oriented framing of the Five Freedoms toward a recognition that good welfare requires opportunities for positive behavioral engagement [6,7]. The Dynamic Animal Welfare Concept similarly emphasizes the animal's capacity to interact with and adapt to its environment as a component of positive welfare, proposing that an individual is in a good welfare state when it has the opportunity to respond appropriately to environmental stimuli and to attain situations it perceives as positive [8]. For horses, whose behavioral repertoire in naturalistic conditions includes prolonged foraging, selective use of different microhabitats, and spatially organized social behavior [9,10], the gap between what managed environments typically provide and what positive welfare requires can be considerable.

Environmental enrichment offers one route to closing that gap, and a substantial body of evidence demonstrates that the provision of structural features, such as foraging opportunities, shelter, varied substrates, and combined spatial complexity, produces measurable improvements in welfare across behavioral, physiological, and molecular indicators [4,11]. It could be argued, therefore, that it is not the mere provision of resources but their spatial distribution across the environment that determines how horses engage with them. Research has shown that enrichment is fundamentally about providing opportunities for animals to acquire information through active engagement with their environment, and that the effectiveness of enrichment depends on the degree to which it enables animals to make choices and exercise behavioral agency [12].

This principle is borne out empirically in equine housing research. It was found that introducing foraging opportunity into a bare paddock restructured horses' entire behavioral time budget, with affiliative interactions increasing and stress-related locomotion decreasing as horses gained spatially distinct locations to engage with [13]. Additional work has shown that the strategic placement of feed, water, and shelter was the single most influential factor determining how horses distributed themselves across a pasture [14]. Similarly, dynamic feeder systems that require movement to access hay consistently increase daily distance travelled and can improve body condition in confined horses [15,16]. However, pasture track systems lacking strategic resource distribution produced no additional movement compared to conventional pastures [17]. A study monitoring young Warmblood horses in a Swedish nature reserve showed the selective association of specific landscape features with specific behavioral states, with individual preferences for particular features emerging clearly when a sufficiently varied environment was available [18]. What these findings suggest, collectively, is that spatial structure, i.e., the presence of differentiated landscape elements that give horses something specific to seek out, is the active ingredient in environmental enrichment rather than space or resources per se.

Small landscape features such as trees, hedges, sand pits, and forage stations offer a pragmatic means of introducing this spatial structure into managed yard environments without fundamentally disrupting existing management systems [19]. Their potential is likely to be most fully realized as equine yards gain broader recognition as contributors to

ecological goals [20]. Importantly, such features also carry potential co-benefits for local biodiversity: even minor additions of structural complexity to grazing land have been shown to yield disproportionate gains in plant species richness, invertebrate diversity, and habitat heterogeneity [21,22]. A landscape design approach that enriches the behavioral environment for horses therefore also moves toward the kind of habitat heterogeneity that local nature organizations and land use policy increasingly require [23,24]. It addresses both welfare and ecological goals through the same intervention, therefore avoiding the type of land use conflicts or management burdens that more extensive approaches might entail.

To date, however, relatively little is known about how horses actually use specific landscape features in managed yard settings, or whether the behavior-specific spatial organization observed in more naturalistic environments also emerges under typical Dutch management conditions. Advances in integrated sensor technology, combining high-resolution GPS, accelerometers, and gyroscopes, have made it possible to monitor fine-scale movement and behavioral state continuously across large datasets [9,18,25], enabling the kind of spatially resolved behavioral analysis that this question requires. Therefore, the present study aimed to investigate how horses use different landscape features across four enriched equine yards in the Netherlands, and to examine whether landscape use was shaped by behavioral state and time of day.

2. Methods

2.1. Study Design

This study was set up as a prospective observational cohort study. Behavioral observations were collected at four equine facilities ('Yards A–D') in the Netherlands, all within the temperate maritime climate zone of northwest Europe. Data collection took place during April and May 2025. The horses at each yard were observed over ten consecutive days on a staggered schedule, maintaining seasonal consistency in daylight hours, weather conditions, and vegetation growth across the observation period.

The study received ethical approval from the Animal Welfare Body of Van Hall Larenstein University of Applied Sciences, dossier number L.2414_25.

2.2. Study Sites

The four yards differed in spatial layout and structural complexity of the turnout area. Yard A represented a naturalistic enriched turnout area and pasture, Yard B an enriched pasture system, and Yards C and D conventional pasture systems, with more detailed descriptions below in order of decreasing complexity. Landscape feature availability differed between yards, yet all included water points and shelter elements (Table 1). No experimental treatments or environmental modifications were introduced during the observation period. Horses remained in their usual housing conditions throughout, ensuring familiarity with both the social group and the physical environment. Horses at all four yards were kept outside 24 hours a day. Individual horses were removed from the group throughout the day for approximately 60–90 minutes at a time, in order to be ridden, groomed, or engage in similar activities. Any sensor recordings during those periods were not included in the data analysis.

Table 1: Spatial availability of landscape features per yard.

Yard	Landscape feature	Area (m ²)	Availability
Yard A	Hedge row west	2,634.24	0.249
	Forage station top	26.36	0.002
	Forage station middle	26.36	0.002
	Shelter left	50.99	0.005
	Grassland surrounded by trees	347.66	0.033
	Water	17.63	0.002
	Passage	1,193.66	0.113
	Hillock	467.40	0.044
	Forage station bottom	26.36	0.002
	Open landscape south	3,162.48	0.298
	Edible plants	56.85	0.005
	Sand pit	75.65	0.007
	Open landscape north	2,513.38	0.237
	Total accessible area	10,599.02	1.000
Yard B	Tree-covered passage	1,000.49	0.027
	Open landscape	16,481.67	0.440
	Trees with undergrowth south	619.31	0.017
	Grassland surrounded by trees	14,870.96	0.397
	Trees with undergrowth north	3,400.89	0.091
	Water center	19.03	0.001
	Water side	19.03	0.001
	Sandy entry passage	1,077.61	0.029
	Total accessible area	37,488.99	1.000
Yard C	Sheltered sand pit	56.90	0.007
	Sandy entry passage	781.15	0.100
	Water	19.36	0.002
	Forage station	23.04	0.003
	Open landscape	6,939.94	0.887
	Total accessible area	7,820.38	1.000
Yard D	Water	33.79	0.005
	Forage station	23.04	0.004
	Individual tree bottom right	35.02	0.005
	Individual tree bottom left	34.57	0.005
	Open landscape	6,334.65	0.978
	Individual tree top right	8.35	0.001
	Individual tree top left	7.52	0.001
	Total accessible area	6,476.93	1.000

Note: Availability represents the proportional area of each feature relative to the total accessible area of the yard. Values are used as a_i in the Manly Selection Ratio calculation.

2.2.1. Yard A — Naturalistic Enriched Turnout Area

Yard A comprised a structurally diverse turnout area of 10,599.02 m². The spatially irregular layout featured thirteen different landscape features. Visual and functional subdivision was created through natural and constructed elements including a separate grassy area surrounded by trees, a hillock, a sandy area surrounded by edible greenery, edible hedgerows, and pasture areas. Roughage was provided via three hay stations distributed across the area (**Figure 1**).

2.2.2. Yard B — Enriched Pasture System

Yard B encompassed 37,488.99 m² and consisted of two large interconnected grassy fields interspersed with natural forest, accounting for over 80% of the accessible area. The wooded area featured underbrush of varying density, providing visual subdivision and natural shade, and created a semi-enclosed corridor between the two main open spaces. Horses moved freely between sections. A designated bare-ground sandy passage included two automatic water troughs. The overall layout offered moderate spatial complexity through variation in elevation, vegetation density, and surface type (**Figure 2**).

2.2.3. Yards C and D — Conventional Pasture

Yards C and D were part of the same facility, divided into two approximately equal sections of pasture (C = 7,820.38 m²; D = 6,476.93 m²). Both were dominated by a single Open landscape feature, accounting for 88.7% (Yard C) and 97.8% (Yard D). Each subsection included one automatic water trough, a single hay rack, and basic shelter in the form of a man-made shelter structure (Yard C) and individual trees (Yard D) (**Figure 3**).

Landscape availability for each yard was quantified by measuring the surface area (m²) of each accessible landscape feature within the turnout area (**Table 1**). These values were used to calculate proportional feature availability for the selection analysis.

2.3. Participating Horses

A total of 30 horses were recruited for data collection: Yard A, n = 6 (4 mares and 2 geldings, mean age 13.5 years; 1,767 m² accessible space per horse); Yard B, n = 12 (7 mares and 5 geldings, mean age 15.5 years; 3,124 m² accessible space per horse); Yard C, n = 6 (6 mares, mean age 13.3 years; 1,303 m² accessible space per horse); Yard D, n = 6 (6 mares, mean age 16.8 years; 1,080 m² accessible space per horse). In all four study sites, the available space per horse substantially exceeded levels reported to permit horses in stable social groups to regulate inter-individual distances through voluntary spacing [26,27]. All horses were selected on the basis of apparent soundness and the absence of visible injuries, lameness, or ongoing medical treatment at the time of inclusion and were kept in well-established, stable social groups. Brief clinical examinations were conducted at the start of the study under veterinary supervision to confirm that horses were free of injury or illness. Horses remained under veterinary supervision throughout, with daily welfare checks performed by either the site manager or the data collection student. All findings were recorded, and any significant deviation from normal behavior was followed up by a veterinarian.

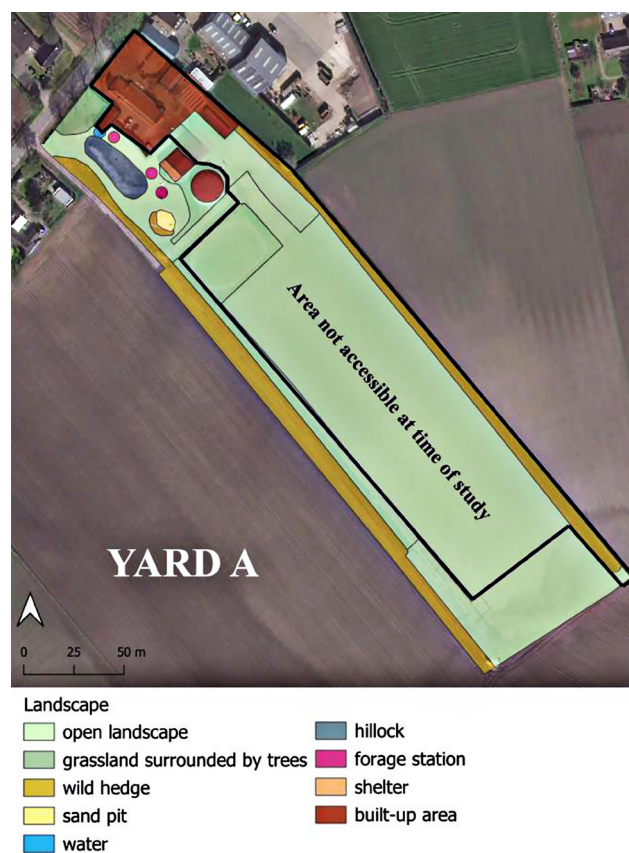


Figure 1: ArcGIS representation of Yard A.

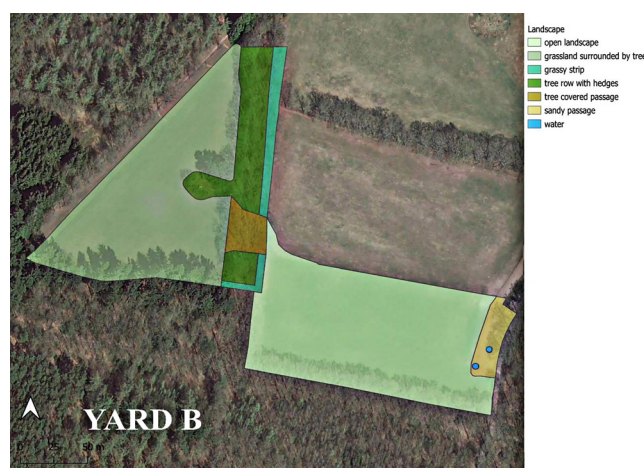


Figure 2: ArcGIS representation of Yard B.



Figure 3: ArcGIS representation of Yards C and D.

2.4. Behavioral Monitoring

All horses were equipped with a Hoofstep® monitoring unit, a lightweight sensor (149 g; dimensions: 96 × 47 × 45 mm) incorporating a GPS receiver, accelerometer, gyroscope, and radio transmitter. The device has been used previously in behavioral studies of horses [18,25]. Monitoring units were mounted on the horse's forehead using softshell headcollars designed with a safety release mechanism to minimize the risk of injury should the horse become caught on an object.

Each unit was connected wirelessly to a base station positioned just outside the enclosure of each yard. Movement and positional data were recorded continuously and transmitted in real time to a cloud-based platform for processing. In the event that the connection to the base station was lost, data were stored locally on each unit on a designated SD card for up to 72 hours. Once the connection to the base station was reestablished, locally stored data were uploaded to the base station.

Using input from both the accelerometer and gyroscope, behavioral classification was performed automatically through an AI-based algorithm trained on a validated equine ethogram [28]. Behavioral activity was categorized into four mutually exclusive behavioral states. *Eating* referred to time spent chewing or swallowing, regardless of body position or concurrent minor movements. *Resting* included periods when the horse was stationary and not engaged in other identifiable behaviors; no distinction was made between standing and lying rest. *Active* included behaviors involving slow locomotion, such as walking, or moderate movement. *Highly active* represented fast locomotor activities such as trotting, cantering, jumping, or energetic movements including headshaking or pawing [25]. Continuously recorded behavioral data were exported as percentages per hour, reflecting the duration of each unique behavior. The data were then aggregated to represent the time (in hours) each horse spent performing a given behavior within a specific landscape feature and time-of-day category.

2.5. Data Preparation

Spatial preprocessing of the full dataset was conducted in Python, with ArcGIS Pro v.3.5.2 used for cartographic checking. The original dataset, containing 506,882 records, was imported into Python (version 3.12) and processed using the pandas [29] and numpy [30] libraries within a Google Colab environment. All data preparation and analysis code was fully annotated to ensure transparency and reproducibility.

Data were screened to remove duplicate timestamp entries generated during the merging of GPS and behavioral classification streams, overlapping behavioral segments, and GPS observations that could not be reliably assigned to a landscape feature. Yards C and D, which were part of the same facility, were separated using feature ID mapping to ensure that each horse was retained only within its correctly assigned terrain section. Records associated with landscape features designated as non-accessible were removed.

To reduce noise from insufficiently sampled individuals, horses with less than 100 hours of recorded behavioral observations were excluded from the analysis to reduce noise and improve model fit. No horses were removed from Yard B. One horse was removed from Yard A due to sensor loss. Two

horses were removed from Yard C, while one horse was removed from Yard D due to insufficient observations recorded (less than 100 hours), resulting in a total of 3,856.50 hours of behavioral data for analysis.

A total of 26 horses were included in the final dataset (Yard A, n = 5; Yard B, n = 12; Yard C, n = 4; Yard D, n = 5). The descriptive overview of equine characteristics can be found in Table 2. Horses were observed across multiple days and time periods. Behavioral observations were recorded together with the landscape feature in which the behavior occurred.

2.6. Calculation of Landscape Feature Preference

Landscape feature use was quantified separately per yard using Manly's Selection Ratios (MSR), which compare observed use of a feature to its proportional availability within the environment [31]. For each landscape feature, the selection ratio w_i was calculated as:

$$w_i = u_i / a_i$$

where u_i represents the proportion of time the horse spent performing a behavior in landscape feature i relative to its total time spent performing that behavior under the given environmental conditions, and a_i represents the proportional availability of landscape feature i relative to the total accessible area of the yard. Selection ratios were calculated for each horse, behavior, landscape feature, and time-of-day category. A ratio greater than 1 indicates selection, a ratio equal to 1 indicates proportional use, and a ratio less than 1 indicates avoidance.

Time of day was categorized into four periods: morning (06:00–11:59), afternoon (12:00–17:59), evening (18:00–23:59), and night (00:00–05:59). Proportional availability a_i was derived from the surface area of each accessible landscape feature divided by the total accessible area of the yard, calculated separately for each yard. Selection ratios were log-transformed ($\log(\text{MSR} + 0.001)$) to reduce skewness and stabilize variance prior to inferential analysis.

2.7. Statistical Analysis

Data preparation and MSR calculation were performed in Python (version 3.12) using pandas [29] and numpy [30] in a Google Colab environment. MSR values were bounded at zero and right-skewed; thus, they were log-transformed prior to statistical analysis. A constant of 0.001 was added before transformation to allow zero-use observations to be retained in the analysis.

Landscape use patterns were analyzed in R version 4.6.0 in a Google Colab environment. Linear mixed models (LMMs) were fitted separately per yard. Each model used the lme4 package [32] with restricted maximum likelihood (REML) estimation and the bobyqa optimizer.

To test the impact of behavioral and temporal variation on landscape feature selection, a three-way interaction model was specified for each yard:

$$\log(\text{MSR}) \sim \text{Behavior} \times \text{Landscape feature} \times \text{Time of day} + (1 \mid \text{Horse})$$

The three-way interaction was not retained as the final analytical structure because it was not significant across yards

and produced a less parsimonious model. To allow direct comparison across yards, the final models therefore retained all two-way interactions:

$\log(\text{MSR}) \sim \text{Behavior} \times \text{Landscape feature} + \text{Behavior} \times \text{Time of day} + \text{Landscape feature} \times \text{Time of day} + (1 \mid \text{Horse})$

A random intercept for Horse accounted for repeated measures and individual variation in baseline selection. Reference categories were set to Eating for Behavior, Afternoon for Time of day, and Open landscape (Open landscape North for Yard A) for Landscape Feature.

Convergence and singularity were assessed using lme4 diagnostics. Type III F-tests with Satterthwaite-approximated degrees of freedom were obtained using the lmerTest package [33]. Marginal R^2 (variance explained by fixed effects) and conditional R^2 (variance explained by fixed and random effects combined) were calculated using the MuMIn package [34]. Where significant interactions were retained, estimated marginal means were derived using the emmeans package [35], where pairwise comparisons were required. Model assumptions were assessed through residual diagnostic plots. Statistical significance was set at $\alpha = 0.05$.

Table 2: Descriptive characteristics of study horses across yards.

Location	Sex	ID	Age at time of study	Height	Breed
Yard A	Mare	YA_1	7.00	164	KWPN
Yard A	Mare	YA_2	6.00	164	KWPN
Yard A	Mare	YA_3	25.00	177	KWPN
Yard A	Gelding	YA_4	21.00	101	Shetland Pony
Yard A	Gelding	YA_5	11.00	114	Welsh Mountain Pony
Mean			13.5	145	
Yard B	Mare	YB_1	15.00	175	KWPN
Yard B	Mare	YB_2	20.00	173	KWPN
Yard B	Mare	YB_3	23.00	162	KWPN
Yard B	Mare	YB_4	9.00	151	French Riding Pony
Yard B	Mare	YB_5	2.00	139	Belgian New Forest Pony
Yard B	Mare	YB_6	24.00	137	New Forest Pony
Yard B	Mare	YB_7	7.00	140	Polish Konik
Yard B	Gelding	YB_8	11.00	165	Unknown
Yard B	Gelding	YB_9	18.00	176	KWPN
Yard B	Gelding	YB_10	13.00	147	Irish Cob
Yard B	Gelding	YB_11	18.00	150	Irish Sport Pony
Yard B	Gelding	YB_12	26.00	180	Holsteiner Warmblood
Mean			15.50	157.9	
Yard C	Mare	YC_1	9.00	154	NRPS
Yard C	Mare	YC_2	8.00	163	KWPN
Yard C	Mare	YC_3	13.00	164	Friesian
Yard C	Mare	YC_4	16.00	170	KWPN
Mean			11.5	162.8	
Yard D	Mare	YD_1	19.00	167	KWPN
Yard D	Mare	YD_2	16.00	165	KWPN
Yard D	Mare	YD_3	18.00	161	KWPN
Yard D	Mare	YD_4	18.00	166	KWPN
Yard D	Mare	YD_5	14.00	163	KWPN
Mean			17	164.4	

3. Results

The final dataset comprised 3,856.5 hours of behavioral observations across 26 horses distributed over four yards (Yard A: 835.1 h; Yard B: 1,880.5 h; Yard C: 574.1 h; Yard D: 566.9 h). An overview of individual observation hours and behavioral time-budget distributions per horse and yard is provided in Table S1 (**Supplementary Materials**).

3.1. Effects of Behavior and Landscape Features: Yard A

3.1.1. Model Fit and Convergence

The mixed model for Yard A converged but showed a singular fit (between-horse variance = 0.000, between-horse SD = 0.000, ICC = 0.000). The model showed good fit (AIC = 4426.75, BIC = 4931.34), with marginal $R^2 = 0.645$ and conditional $R^2 = 0.645$. See **Figure 4** for a depiction of variances between individual horses across behaviors.

3.1.2. Main Effects

Type III tests of fixed effects showed that Behavior ($F(3,940) = 16.979$, $P < 0.001$); Time of day ($F(3,940) = 7.273$, $P < 0.001$), and Landscape feature ($F(12,940) = 98.199$, $P < 0.001$) were significant predictors of log MSR. Significant main-effect parameter estimates relative to the reference categories (Eating, Afternoon, Open landscape North) are shown in **Table 3**.

3.1.3. Two-Way Interactions

Significant two-way interactions were observed for Behavior $\times$ Landscape feature ($F(36,940) = 4.502$, $P < 0.001$) and Landscape feature $\times$ Time of day ($F(36,940) = 12.779$, $P < 0.001$). The significant parameter estimates from the retained two-way interaction terms are presented in **Table 4**.

Figure 5 visualizes the corresponding distribution of MSR values across landscape features and behaviors. Temporal patterns in landscape feature use and behavior are shown in Figure S1 and Figure S2, respectively (**Supplementary Materials**).

3.2. Effects of Behavior and Landscape Features: Yard B

3.2.1. Model Fit and Convergence

The mixed model for Yard B showed normal convergence with a non-singular fit (between-horse variance = 0.414, between-horse SD = 0.643, ICC = 0.085). The model showed moderate fit (AIC = 6854.81, BIC = 7212.39), with marginal $R^2 = 0.496$ and conditional $R^2 = 0.539$. See **Figure 6** for a depiction of variances between individual horses across behaviors.

3.2.2. Main Effects

Type III tests of fixed effects showed that Behavior ($F(3,1460) = 12.308$, $P < 0.001$); Time of day ($F(3,1460) = 75.281$, $P < 0.001$), and Landscape feature ($F(7,1460) = 124.663$, $P < 0.001$) were all significant predictors of log MSR. Significant main-effect parameter estimates relative to the reference categories (Eating, Afternoon, Open landscape) are shown in **Table 5**.

3.2.3. Two-Way Interactions

Significant two-way interactions were observed for Behavior $\times$ Landscape feature ($F(21,1460) = 2.710$, $P < 0.001$);

Behavior $\times$ Time of day ($F(9,1460) = 2.877$, $P = 0.002$); and Landscape feature $\times$ Time of day ($F(21,1460) = 20.671$, $P < 0.001$). **Table 6** displays the significant parameter estimates from the retained two-way interaction terms, while **Figure 7** illustrates the distribution of MSR values across landscape features and behaviors. Figure S3 and Figure S4 show temporal patterns in landscape feature use and behavior (**Supplementary Materials**).

3.3. Effects of Behavior and Landscape Features at Yard C

3.3.1. Model fit and convergence

The mixed model for Yard C showed normal convergence with a non-singular fit (between-horse variance = 0.140, between-horse SD = 0.374, ICC = 0.026). The model showed moderate fit (AIC = 1508.88, BIC = 1682.22), with marginal $R^2 = 0.350$ and conditional $R^2 = 0.367$. See **Figure 8** for a depiction of variances between individual horses across behaviors.

3.3.2. Main Effects

Type III tests of fixed effects showed that Behavior ($F(3,273) = 4.191$, $P = 0.006$) and Landscape feature ($F(4,273) = 19.326$, $P < 0.001$) were significant on log MSR. Time of day was non-significant ($F(3,273) = 2.356$, $P = 0.072$). Significant main-effect parameter estimates relative to the reference categories (Eating, Afternoon, Open landscape) are shown in **Table 7**.

3.3.3. Two-Way Interactions

Significant two-way interactions were observed for Behavior $\times$ Landscape feature ($F(12,273) = 4.090$, $P < 0.001$) and Landscape feature $\times$ Time of day ($F(12,273) = 2.113$, $P = 0.016$). The significant parameter estimates from the retained two-way interaction terms are shown in **Table 8**, with **Figure 9** visualizing the distribution of MSR values for behaviors across different landscape features. Figure S5 and Figure S6 visualize temporal patterns in, respectively, landscape feature use and behavior (**Supplementary Materials**).

3.4. Effects of Behavior and Landscape Features at Yard D

3.4.1. Model Fit and Convergence

The mixed model for Yard D showed normal convergence with a non-singular fit (between-horse variance = 0.179, between-horse SD = 0.423, ICC = 0.020). The model showed moderate fit (AIC = 2887.31, BIC = 3146.99), with marginal $R^2 = 0.362$ and conditional $R^2 = 0.375$. See **Figure 10** for a depiction of variances between individual horses across behaviors.

3.4.2. Main Effects

Type III tests of fixed effects showed that, for Yard D, Landscape feature was significant ($F(6,498) = 38.691$, $P < 0.001$), while behavior ($F(3,498) = 0.982$, $P = 0.401$) and Time of day ($F(3,498) = 2.592$, $P = 0.052$) were non-significant on log MSR. Significant main-effect parameter estimates relative to the reference categories (Eating, Afternoon, Open landscape) are shown in **Table 9**.

3.4.3. Two-Way Interactions

Significant two-way interactions were observed for Behavior $\times$ Landscape feature ($F(18,498) = 2.504$, $P < 0.001$). Significant parameter estimates from the retained two-way interaction terms are reported in **Table 10**, and the corresponding distributions of MSR values across landscape features and

behaviors are shown in **Figure 11**. Corresponding temporal patterns in landscape feature use and behavior are provided in Figure S7 and Figure S8 (**Supplementary Materials**).

An overview of mean MSR values per landscape feature $\times$ behavior combination across all four yards is provided in Table S2 (**Supplementary Materials**).

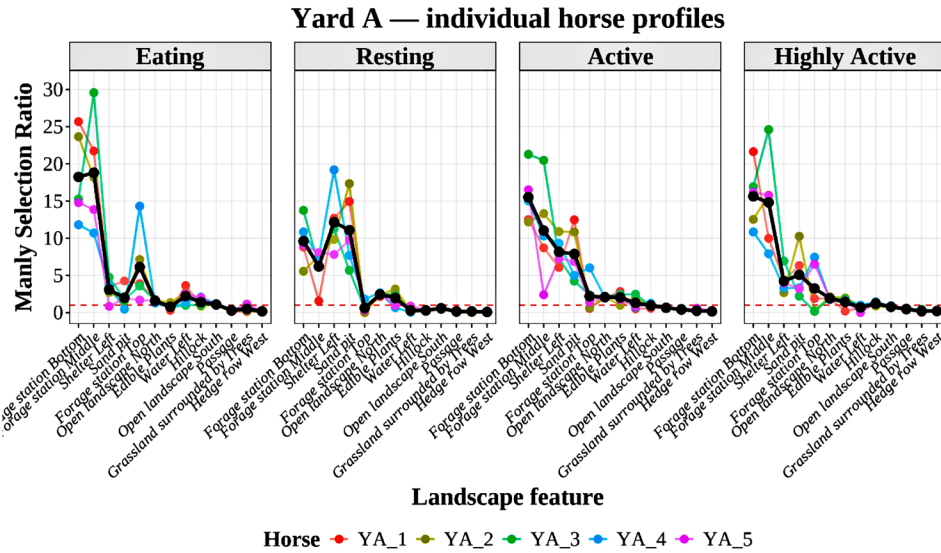


Figure 4: Individual landscape feature use Manly Selection Ratio (MSR) across behaviors for Yard A.

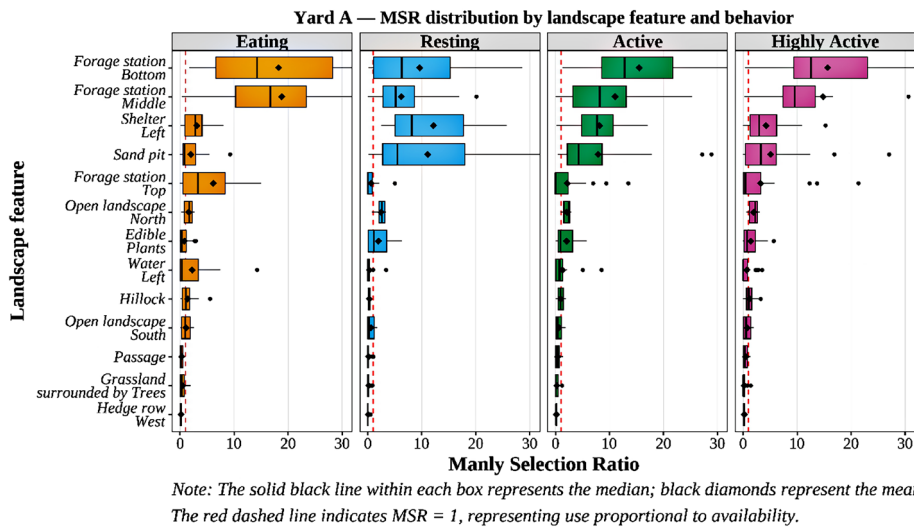


Figure 5: Mean Manly Selection Ratios (MSR) for behavior across different landscape features for Yard A, with values > 1 indicating preferences, values $= 1$ indicating neutral use, and values < 1 indicating avoidance. Boxes show the interquartile range; diamond = mean; dashed line = MSR = 1.

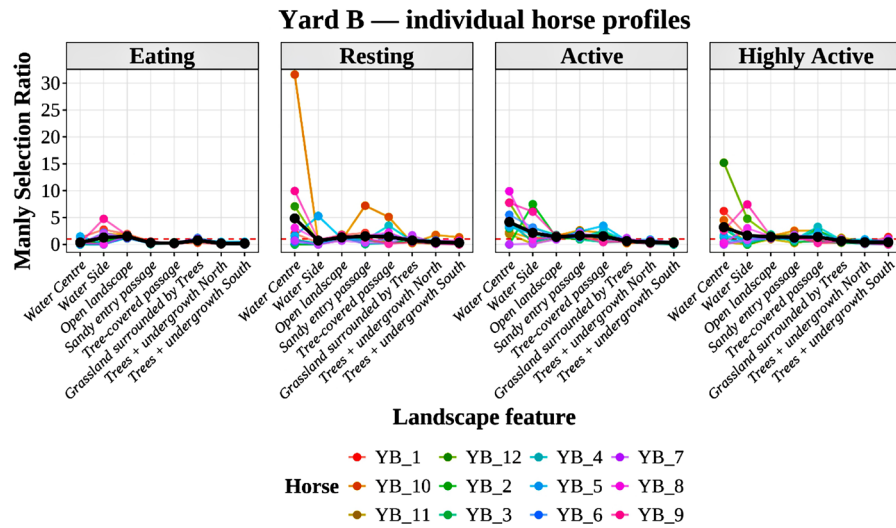


Figure 6: Individual landscape feature use Manly Selection Ratio (MSR) across behaviors for Yard B.

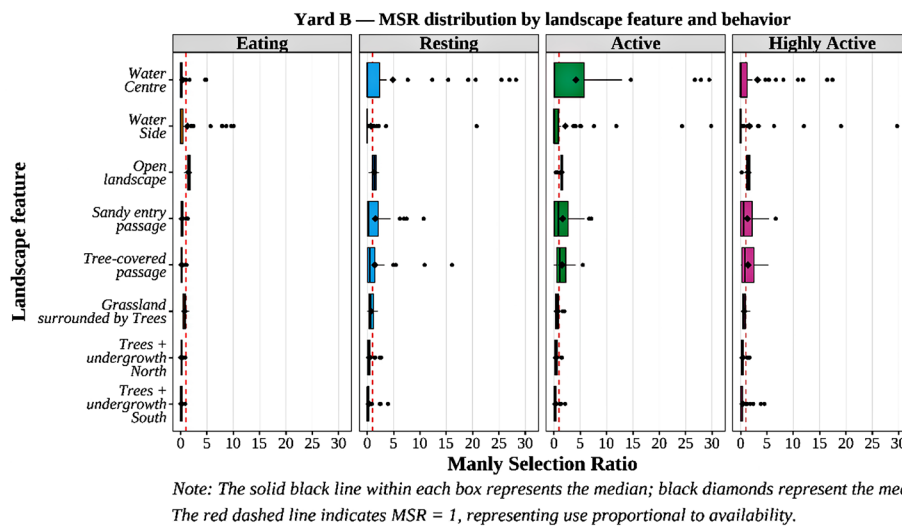


Figure 7: Mean Manly Selection Ratios (MSR) for behavior across different landscape features for Yard B, with values > 1 indicating preferences, values = 1 indicating neutral use, and values < 1 indicating avoidance. Boxes show the interquartile range; diamond = mean; dashed line = MSR = 1.

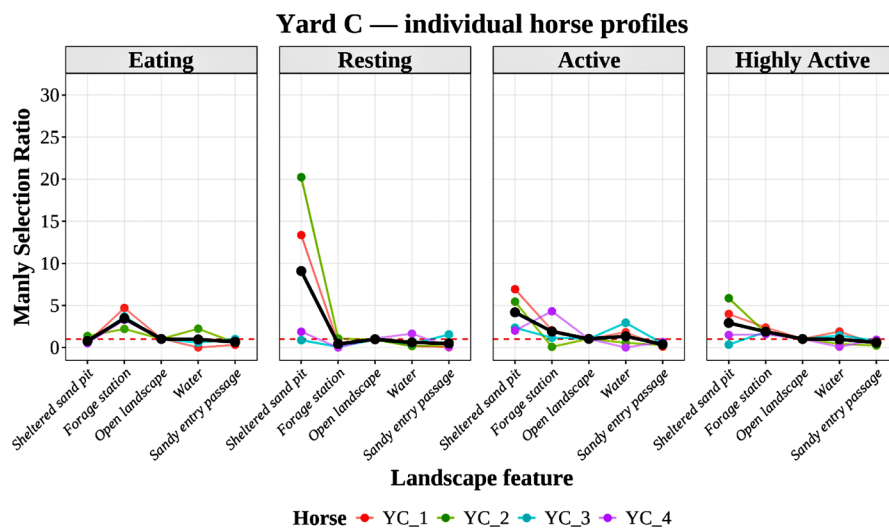


Figure 8: Individual landscape feature use Manly Selection Ratio (MSR) across behaviors for Yard C.

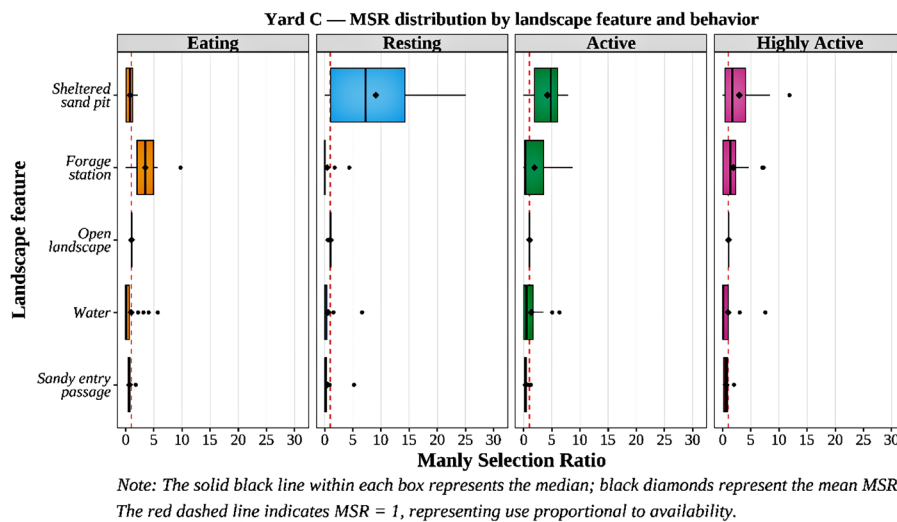


Figure 9: Mean Manly Selection Ratios (MSR) for behavior across different landscape features for Yard C, with values > 1 indicating preferences, values = 1 indicating neutral use, and values < 1 indicating avoidance. Boxes show the interquartile range; diamond = mean; dashed line = MSR = 1.

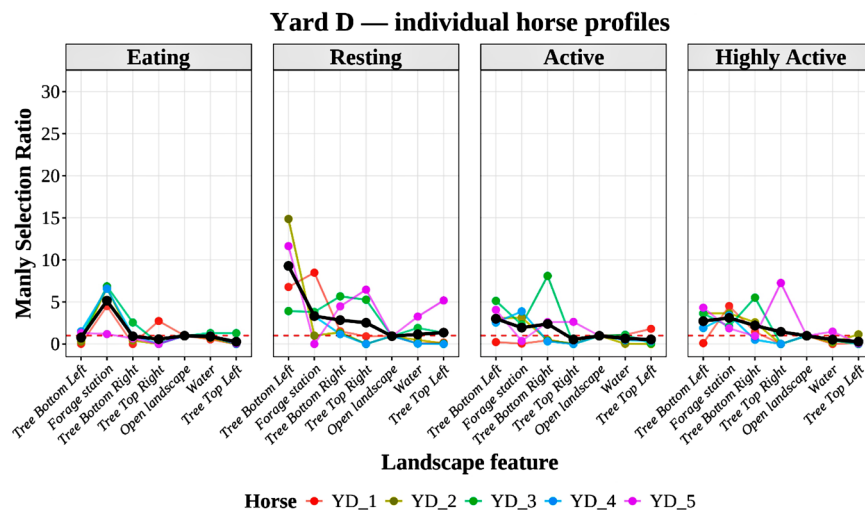


Figure 10: Individual landscape feature use Manly Selection Ratio (MSR) across behaviors for Yard D.

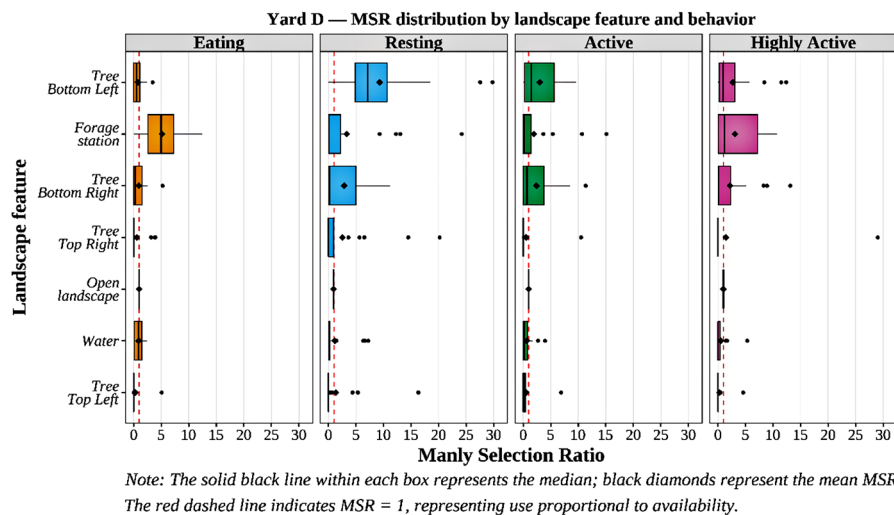


Figure 11: Mean Manly Selection Ratios (MSR) for behavior across different landscape features for Yard D, with values > 1 indicating preferences, values = 1 indicating neutral use, and values < 1 indicating avoidance. Boxes show the interquartile range; diamond = mean; dashed line = MSR = 1.

Table 3: Significant main effects relative to the reference category (Eating, Afternoon, Open landscape North) in Yard A.

Parameter	B	SE	<i>t</i>	<i>P</i>	95% CI lower	95% CI upper
Edible plants	-2.51	0.77	-3.26	0.001	-4.02	-1
Forage station bottom	2	0.77	2.59	0.010	0.48	3.51
Forage station middle	2.08	0.77	2.7	0.007	0.57	3.59
Hedge row west	-2.01	0.77	-2.61	0.009	-3.52	-0.5
Passage	-1.53	0.77	-1.98	0.048	-3.04	-0.02
Water left	-1.59	0.77	-2.07	0.039	-3.11	-0.08

Table 4: Significant parameter estimates from the retained two-way interactions relative to the reference category (Eating, Afternoon, Open landscape North) in Yard A.

Parameter	B	SE	<i>t</i>	<i>P</i>	95% CI lower	95% CI upper
Resting × forage station bottom	-1.72	0.82	-2.09	0.037	-3.33	-0.1
Resting × forage station middle	-2.01	0.82	-2.44	0.015	-3.63	-0.4
Resting × forage station top	-4.84	0.82	-5.88	< 0.001	-6.46	-3.23
Active × forage station top	-3.33	0.82	-4.04	< 0.001	-4.94	-1.71
Highly active × forage station top	-2.22	0.82	-2.69	0.007	-3.83	-0.6
Resting × grassland surrounded by trees	-1.93	0.82	-2.34	0.019	-3.54	-0.31
Resting × hedge row west	-2.41	0.82	-2.93	0.003	-4.03	-0.8
Resting × hillock	-2.2	0.82	-2.68	0.008	-3.82	-0.59
Resting × open landscape south	-2.41	0.82	-2.93	0.003	-4.03	-0.8
Resting × passage	-1.8	0.82	-2.19	0.029	-3.41	-0.18
Resting × water left	-3.02	0.82	-3.67	< 0.001	-4.64	-1.41
Highly active × water left	-2.05	0.82	-2.49	0.013	-3.67	-0.44
Highly active × evening	-1.12	0.46	-2.45	0.014	-2.01	-0.22
Forage station top × morning	-1.77	0.82	-2.15	0.032	-3.38	-0.15
Grassland surrounded by trees × morning	-3.93	0.82	-4.77	< 0.001	-5.54	-2.31
Open landscape south × evening	-4.63	0.82	-5.62	< 0.001	-6.24	-3.01
Passage × evening	-4.02	0.82	-4.89	< 0.001	-5.64	-2.41
Water left × evening	-1.85	0.82	-2.25	0.025	-3.47	-0.24
Grassland surrounded by trees × night	-4.04	0.82	-4.91	< 0.001	-5.66	-2.43
Hedge row west × night	-2.3	0.82	-2.8	0.005	-3.92	-0.69
Open landscape south × night	-2.64	0.82	-3.2	0.001	-4.25	-1.02
Passage × night	-3.94	0.82	-4.78	< 0.001	-5.55	-2.32
Shelter left × night	-1.86	0.82	-2.26	0.024	-3.48	-0.25
Water left × night	-2.38	0.82	-2.9	0.004	-4	-0.77

Table 5: Significant main effects relative to the reference category (Eating, Afternoon, Open landscape) in Yard B.

Parameter	B	SE	<i>t</i>	<i>P</i>	95% CI lower	95% CI upper
Sandy entry passage	-1.34	0.57	-2.35	0.019	-2.45	-0.22
Tree-covered passage	-2.74	0.57	-4.83	< 0.001	-3.86	-1.63
Trees with undergrowth north	-2.91	0.57	-5.11	< 0.001	-4.02	-1.79
Trees with undergrowth south	-3.73	0.57	-6.56	< 0.001	-4.84	-2.61
Water center	-3.13	0.57	-5.5	< 0.001	-4.24	-2.01
Water side	-4.4	0.57	-7.75	< 0.001	-5.52	-3.29

Table 6: Significant parameter estimates from the retained two-way interactions relative to the reference category (Eating, Afternoon, Open landscape) in Yard B.

Parameter	B	SE	<i>t</i>	<i>P</i>	95% CI lower	95% CI upper
Resting × tree-covered passage	1.36	0.61	2.24	0.025	0.17	2.55
Active × tree-covered passage	2.64	0.61	4.35	< 0.001	1.45	3.83
Highly active × tree-covered passage	2.24	0.61	3.68	< 0.001	1.04	3.43
Resting × water center	1.57	0.61	2.58	0.010	0.37	2.76
Active × water center	2.03	0.61	3.34	< 0.001	0.84	3.22
Active × evening	-1.18	0.43	-2.75	0.006	-2.02	-0.34
Highly active × evening	-0.85	0.43	-1.97	0.049	-1.69	0
Resting × night	-0.94	0.43	-2.2	0.028	-1.79	-0.1
Active × night	-1.72	0.43	-4	< 0.001	-2.56	-0.87
Highly active × night	-0.85	0.43	-1.97	0.049	-1.69	0
Water side × morning	2.6	0.61	4.28	< 0.001	1.41	3.79
Sandy entry passage × evening	-3.3	0.61	-5.44	< 0.001	-4.49	-2.11
Water center × evening	-4.38	0.61	-7.22	< 0.001	-5.58	-3.19
Water side × evening	-2.23	0.61	-3.67	< 0.001	-3.42	-1.04
Sandy entry passage × night	-2.89	0.61	-4.75	< 0.001	-4.08	-1.69
Trees with undergrowth north × night	1.29	0.61	2.12	0.034	0.1	2.48
Water center × night	-4.44	0.61	-7.3	< 0.001	-5.63	-3.25
Water side × night	-1.61	0.61	-2.64	0.008	-2.8	-0.41

Table 7: Significant main effect relative to the reference category (Eating, Afternoon, Open landscape) in Yard C.

Parameter	B	SE	<i>t</i>	<i>P</i>	95% CI lower	95% CI upper
Water	-2.28	1.07	-2.14	0.033	-4.38	-0.18

Table 8: Significant parameter estimates from the retained two-way interactions relative to the reference category (Eating, Afternoon, Open landscape) in Yard C.

Parameter	B	SE	<i>t</i>	<i>P</i>	95% CI lower	95% CI upper
Resting × Forage station	−5.1	1.14	−4.48	< 0.001	−7.34	−2.86
Resting × Sheltered sand pit	2.33	1.14	2.04	0.042	0.08	4.57

Table 9: Significant main effects relative to the reference category (Eating, Afternoon, Open landscape) in Yard D.

Parameter	B	SE	<i>t</i>	<i>P</i>	95% CI lower	95% CI upper
Individual tree bottom left	−2.58	1.24	−2.07	0.039	−5.02	−0.13
Individual tree bottom right	−3.32	1.24	−2.67	0.008	−5.76	−0.87
Individual tree top left	−4.41	1.24	−3.55	< 0.001	−6.86	−1.97
Individual tree top right	−5.23	1.24	−4.2	< 0.001	−7.67	−2.78

Table 10: Significant parameter estimates from the retained two-way interactions relative to the reference category (Eating, Afternoon, Open landscape) in Yard D.

Parameter	B	SE	<i>t</i>	<i>P</i>	95% CI lower	95% CI upper
Resting × forage station	−3.34	1.33	−2.51	0.012	−5.95	−0.73
Active × forage station	−3.26	1.33	−2.45	0.015	−5.87	−0.64
Resting × individual tree bottom left	3.49	1.33	2.62	0.009	0.87	6.1
Water × evening	−2.64	1.33	−1.99	0.048	−5.26	−0.03

4. Discussion

The study aimed to investigate how horses use different landscape features across four differently designed turnout areas in the Netherlands, and whether landscape feature use was shaped by behavioral state and time of day.

Across all four turnout areas, a systematic relationship emerged between landscape heterogeneity and the expression of behavior-specific spatial preferences. More specifically, landscape features were not used as interchangeable spaces, but appeared to serve different functional roles depending on behavioral state. In Yard A, the highly differentiated patterns of feature use across behavioral states suggest that horses did not simply use all available features indiscriminately, as evidenced by the high number of statistically significant interactions. Instead, they differentiated between landscape features according to behavioral context: a pronounced concentration of resting behavior in the shelter or the sand pit, and greater feeding-related use of the forage station, as evidenced by high MSR values.

By contrast, Yard B, despite containing multiple natural landscape features and a comparatively large total area, appeared less behaviorally differentiated. Many of its landscape elements consisted of broad, multifunctional zones rather than clearly delineated resources. While heterogeneous in a

physical sense, the turnout area was functionally less specific, with more moderate MSR values. Yards C and D were visually simpler and dominated by open landscape. Nevertheless, both turnout areas afforded some behavior-specific zoning. While the forage station was moderately attractive in both Yards C and D, the sheltered sand pit in Yard C and one of the individual trees in Yard D were proportionally more attractive with MSRs greater than 9. Functionally clear environments, whether created through high heterogeneity or clearly delineated zones, appeared to promote more predictable behavior-specific use of space, whereas less differentiated environments allowed greater individual variation in spatial organization. The findings also suggest that structural complexity alone is insufficient to explain how horses organize their use of space. Instead, the functional clarity, or "legibility," of landscape features appeared equally important [36].

These findings lend support to the theory that horses perceive their environment as a composite of functional spaces, much like a house with different rooms, with each landscape feature serving a distinct purpose in their daily lives [18]. Importantly, the degree to which this functional organization can be expressed depends directly on the structural opportunities each environment provides. Findings also suggest that more functionally differentiated environments may promote greater convergence in how horses allocate behaviors across space.

The present observations were conducted during spring and therefore reflect landscape use under those environmental conditions. Seasonal variation in temperature, weather, and vegetation may influence the use of individual landscape features, for example, by increasing the use of shade or shelter during warmer periods or altering the attractiveness of forage resources. Nevertheless, similar patterns of behavior-specific spatial organization were observed in an independent dataset collected during July and August [18], suggesting that the functional differentiation of landscape features may be relatively robust across seasons. Further research spanning the full annual cycle is nevertheless required to determine how seasonal conditions modify these spatial preferences.

Interestingly, while behavior-specific organization of space was robust across yards, temporal effects were more selective. Most behavior-feature associations remained relatively stable throughout the daily cycle, although certain landscape features showed recurring temporal patterns. Water features in particular appeared to be used more frequently during the later part of the day. Research has shown that horses tend to drink following a meal [37,38]. However, as the horses in the present study had continuous access to forage, this is less likely to explain the observed pattern. It is possible that water features, in addition to providing drinking opportunities, also serve social functions that increase their attractiveness at particular times of day. However, further research is needed to investigate this possibility. Overall, although time of day may modify the use of certain landscape features, the present findings suggest that their functional significance is more closely tied to their structural affordances.

Open landscape occupied the largest proportion of available area across all four turnout areas, yet open space alone appeared insufficient to generate strong behavioral organization. This is noteworthy, as one might intuitively expect horses to use large undifferentiated areas flexibly for multiple behavioral states. Instead, the findings suggest that environments lacking differentiated resources may function less as enriching landscapes and more as spatial background. In welfare terms, this supports the growing recognition that space alone, while necessary, is unlikely to constitute enrichment. Evidence from paddock design research similarly indicates that increasing area improves welfare outcomes only up to a threshold, beyond which additional space produces diminishing returns unless accompanied by structural features that distribute resources and motivate movement [14]. Current findings seem to support this interpretation. Despite providing less accessible space per horse than Yard B, Yard A exhibited significantly more behavior-landscape interactions. Similarly, although Yards C and D provided comparable amounts of accessible space per horse, they differed in the extent to which their landscape features functioned as distinct behavioral "rooms." It therefore appears to be the presence and distribution of differentiated landscape features, rather than spatial extent per se, that drives meaningful behavioral organization. This aligns with broader enrichment literature demonstrating that the spatial distribution of resources, rather than their mere provision, shapes

how horses engage with their environment and supports species-typical behavioral time budgets [10,13].

These findings have implications for how equine welfare is conceptualized and pursued in practice. The Five Domains model has advanced welfare thinking considerably by incorporating positive mental experience as an explicit domain alongside the more traditionally deficit-focused dimensions of nutrition, health, and physical environment [6,7]. The Dynamic Animal Welfare Concept similarly emphasizes the animal's capacity to engage with and adapt to environmental stimuli as a component of good welfare [8]. To date, much of the practical guidance emerging from these frameworks remains largely focused on meeting immediate needs, such as the provision of adequate forage, sufficient space, social housing, or shelter from extremes. These provisions bring welfare to a functional baseline. However, as has been argued in relation to human psychology, the absence of deficit does not constitute flourishing; a genuinely positive state requires conditions that actively support engagement and choice [39]. The parallel to equine welfare science is direct: Providing turnout and companionship establishes the conditions for normal functioning. Structural differentiation of the spatial environment builds on that foundation by creating the conditions under which horses can actively select where and how to meet their behavioral needs at any given moment [12,13,40].

Recent work on environmental enrichment has proposed that enrichment functions by providing animals with opportunities to acquire information through active engagement with their environment [12]. Current findings suggest that landscape heterogeneity may offer a route to positive welfare outcomes by creating a differentiated spatial environment that allows horses to choose, and therefore engage with, functionally distinct options when expressing certain types of behavior [41]. The capacity to make choices and thus exert control over one's environment has been identified as intrinsically rewarding across species [42–44]. Similarly, welfare improvements associated with paddock access reversed rapidly once that access was withdrawn, suggesting that positive behavioral states are contingent on continued environmental opportunity rather than accruing as a stable residual [4]. The current findings extend this logic to spatial design: the degree of behavior-specific spatial organization observed across the four turnout areas was fundamentally influenced by the structural environments provided. Arguably, a landscape that offers meaningful choice only intermittently offers only intermittent opportunity for agency.

These findings underline the importance of landscape design as a conceptually distinct way to positively influence welfare in practical equine management. Even more importantly, perhaps, landscape features such as trees, hedges, sand pits, and forage stations appear sufficient to create the structural diversity that enables meaningful spatial choice and behavioral enrichment [11]. This is consistent with evidence that ecologically modest additions can yield disproportionate improvements in habitat complexity and biodiversity value [21,22,45,46]. The integration of structural landscape features into equine yard design therefore serves a dual purpose: supporting biodiversity goals while expanding the behavioral opportunities available to

individual horses [20,47,48]. As such, the present findings provide empirical support for previously proposed landscape design principles aimed at simultaneously promoting equine welfare, biodiversity, and multifunctional land use [19]. Welfare and landscape ecology are not separate objectives. They are complementary goals, pursued through the same intervention.

4.1. Limitations

Several limitations of the present study warrant consideration. First, data loss due to sensor malfunction, transmission failure, and GPS signal dropout resulted in the exclusion of six horses from the final dataset. While the 100-hour threshold ensured that only adequately sampled individuals were retained, it inevitably reduced statistical power at the yard level, particularly at Yards C and D, where group sizes were already modest. These technical limitations are inherent to field-based sensor studies and are consistent with data attrition rates reported in comparable research [18,25].

Second, although the four yards were selected to represent a meaningful range of structural complexity under ecologically and managerially relevant conditions, they were not experimentally controlled environments. The four turnout areas differed not only in landscape feature availability but also in total area, spatial configuration, and management routine, making direct cross-site comparisons of selection ratios inappropriate. The analytical approach of fitting separate models per yard and focusing on within-yard behavior-feature associations was chosen to respect these differences rather than obscure them. The variation between turnout areas is, in this sense, a feature of the study rather than a flaw: it reflects the real diversity of equine management systems in the Netherlands and strengthens the generalizability of the findings to applied settings.

Third, the horse populations across yards differed in age, breed, and type, reflecting the practical realities of recruiting participants from existing facility groups rather than from a controlled sample. Standardizing horse characteristics across four independently managed facilities was not feasible, and this limits the extent to which between-yard differences in landscape use can be attributed solely to environmental structure.

5. Conclusion

This study demonstrates that horses do not use turnout environments as undifferentiated open space, but organize their spatial behavior in relation to specific landscape features associated with particular activities. Across the four turnout areas, landscape use was consistently shaped by the interaction between behavioral state and environmental structure. While open areas functioned primarily as a spatial matrix, structurally differentiated features such as forage stations, shelters, trees, sand pits, and water points were selectively associated with specific functional states, including eating, resting, and physical activity.

These findings suggest that landscape heterogeneity expands opportunities for horses to express agency through behaviorally meaningful spatial choice. Importantly, the strongest context-dependent patterns emerged in the more

structurally diverse turnout areas, indicating that relatively modest additions of environmental complexity may substantially influence how horses engage with their surroundings.

Ultimately, these findings support a shift from viewing turnout design primarily in terms of space provision toward considering the functional organization of space. Designing landscapes that optimize equine welfare while simultaneously contributing to biodiversity conservation addresses what are arguably two of the most pressing challenges facing the equine sector and the wider society in which it operates.

Supplementary Materials

Table S1: Individual observation hours and behavioral time-budget distributions per horse and yard. Table S2: Mean Manly Selection Ratio (MSR) values per landscape feature × behavior combination across all four yards. Figures S1, S3, S5, and S7: Distribution of Manly Selection Ratios (MSR) across landscape features and time of day for Yards A–D, respectively. Figures S2, S4, S6, and S8: Distribution of Manly Selection Ratios (MSR) across behaviors and time of day for Yards A–D, respectively.

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Authors' Contributions

I.W.: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Supervision. K.V.: Data collection, Writing – review & editing. Y.E.: Data collection, Writing – review & editing, Supervision. M.L.: Data curation. K.F.: Writing – review & editing, Supervision. T.E.: Data curation, Data preparation, Writing – review & editing, Supervision. All authors have read and agreed to the published version of the manuscript.

Data Availability

Data storage was conducted in accordance with the Research Data Management policy framework of the University of Applied Sciences Van Hall Larenstein. Data management adheres to the principles of Open Science, and the data are available upon reasonable request.

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Conflicts of Interest

M.L. and K.F. were employed by HoofStep® during the study and provided the raw data for statistical analysis. I.W., K.V., Y.E., and T.E. have no conflicts of interest to declare.

Ethical Approval

The study received ethical approval from the Animal Welfare Body of Van Hall Larenstein University of Applied Sciences, dossier number L.2414_25. The study was conducted according to the Netherlands Code of Conduct for Research Integrity and followed the guidelines of the Declaration of Helsinki.

Consent to Participate

Written informed consent was obtained from the persons responsible for the horses involved in the study.

Declaration of Generative AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT (GPT-5.5; OpenAI) and Claude Sonnet 4.6 (Anthropic) for language refinement and development of parts of the statistical analysis code. Following the use of these tools, the authors reviewed and edited the content as needed and take full responsibility for the final version of the publication.

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