# Spatial Utilization by Domestic Horses Using GPS Tracking

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ABSTRACT

Domestic horses rely on movement to support physical health, behavioral expression, and welfare, yet opportunities for locomotion are often constrained in managed environments. This study examined how field size, environmental conditions, and daily temporal patterns influence the spatial behavior of domestic horses using four months of continuous GPS tracking at a commercial boarding facility. Horses were turned out in 29 fields ranging from small paddocks to multi-acre pastures under routine management conditions. Field size emerged as the strongest predictor of movement distance, with horses in very small enclosures traveling substantially less than those in moderately sized pastures. Horses also exhibited pronounced daily movement patterns, traveling the greatest distances during daylight, particularly in the afternoon, and the least at night. Weather effects were modest; temperature showed a small positive association with movement, whereas dew point and precipitation did not significantly predict locomotion once time of day and field size were considered. Movement declined in April, a pattern that may reflect management changes, seasonal pasture conditions, or other unmeasured factors. Together, these findings highlight how spatial provision, management routines, and biological rhythms interact to shape locomotor behavior in domestic horses. The results inform welfare-oriented management strategies that prioritize adequate space and demonstrate the value of consumer-grade GPS technology for assessing equine spatial behavior in real-world settings.

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# Introduction

## Equine Behavior and Welfare

The Five Domains Model, originally developed by Mellor and Reid (1994) and later expanded to include positive affective states (Mellor & Beausoleil, 2015; Mellor & Burns, 2020), provides a comprehensive framework for understanding how environmental conditions influence animal welfare. The model emphasizes both the prevention of negative experiences and the promotion of positive ones, such as agency, exploration, and comfort. When applied to horses, it highlights how management and training practices affect opportunities for natural behavior and psychological well-being (Mellor & Burns, 2020).

Horses evolved in expansive, heterogeneous environments characterized by grasslands and seasonal variability in resources—conditions that fostered adaptive movement, vigilance, and flexible social strategies (Waring, 2003; McDonnell, 2003; Miraglia et al., 2008). In unmanaged and feral conditions, horses organize themselves into characteristic herd structures composed of two main social units: harem bands and bachelor groups. Harems typically consist of one stallion, several mares, and their dependent offspring, forming stable groups that provide protection and cooperative care (McDonnell, 2003; Waring, 2003). In contrast, bachelor bands are made up of young or non-breeding stallions that live together in loosely associated groups (Feh, 1999; Torres Borda et al., 2023). These social structures give rise to flexible, loosely organized population-level patterns where groups may fuse, fission, or temporarily associate depending on resource availability and social dynamics.

Daily interactions among horses within groups reflect a repertoire of affiliative behaviors that reinforce social stability, including mutual grooming, synchronized resting, and maintaining spatial cohesion within groups (Hall & Kay, 2024a; Marliani et al., 2021). Such interactions contribute to cooperation, emotional stability, and long-term social partnerships. Affiliative behaviors are central to herd cohesion, as strong bonds facilitate coordinated movement, mitigate conflict, increase safety from threats through vigilance and defense, and enhance resilience in variable environmental conditions.

The Five Domains Model has been specifically applied to the domestic horse (*Equus caballus*) due to a long history of welfare concerns related to management and training practices (Mellor & Burns, 2020). This application demonstrates how the framework can be used to evaluate both the negative impacts of traditional husbandry and the positive opportunities afforded by progressive management practices that support behavioral expression and psychological well-being. Despite thousands of years of domestication, horses have retained these fundamental behavioral needs (Waring, 2003; Brubaker et al., 2021; Torres Borda et al., 2023; Hall & Kay, 2024a). These needs are often summarized as the “three Fs”: friends, forage, and freedom (Fraser, 2008; Hall & Kay, 2024a). When provided with environments that support these natural behaviors, domestic horses display time budgets remarkably like their feral counterparts—spending 60–70% of the day grazing, 20–30% resting, and the remainder engaged in locomotion, vigilance, and social interactions (Maisonpierre et al., 2019; Marliani et al., 2021). Natural patterns of movement are integral to equine welfare, supporting both physical health and psychological resilience (Miraglia et al., 2008; McKeever, 2002; Mellor, 2017).

Research on feral horses has provided a foundation for understanding equine needs. Observations of free-ranging and semi-feral populations have clarified how horses naturally allocate time, organize space, and form social structures under minimal human influence. Most domestic horses, however, live under managed conditions where movement, diet, and daily activities are largely controlled by humans. Common management practices—such as stabling, restricted turnout, concentrated feeding, and fixed schedules—can substantially limit opportunities for natural behavior and voluntary locomotion (Maisonpierre et al., 2019; McGowan et al., 2010). While these practices are often designed for convenience, safety, or pasture preservation, they can inadvertently constrain behavioral expression and impact welfare. Comparing feral and managed systems, therefore, provides valuable insight into how environmental design and husbandry decisions influence horses' physical and psychological well-being.

Managing horses requires attention not only to the animals' health and welfare but also to the sustainability of the land they inhabit. Horses exert substantial pressure on pastures through continuous grazing, trampling, and congregation around preferred sites such as water troughs, hay feeders, and gateways. These pressures degrade vegetation and compact soils, contributing to erosion and a decline in pasture productivity. Poor land conditions, in turn, affect horse welfare by limiting forage quality, increasing exposure to mud-related hoof problems, and reducing opportunities for natural movement. Sustainable equine management, therefore, requires balancing animal needs with stewardship of the land, emphasizing rotational grazing, pasture rest, and careful placement of resources to minimize localized overuse (Hassan-Vásquez et al., 2022; Rivero et al., 2021). By recognizing the interdependence of horse welfare and land health, managers can create environments that support both ecological integrity and the behavioral needs of domestic horses.

Environmental variables, particularly weather, also exert a significant influence on equine behavior and welfare. Horses adapt their movement, grazing, and resting patterns in response to temperature, precipitation, and seasonal changes in daylight (Rivero et al., 2021; Marliani et al., 2021). High temperatures often reduce activity and encourage shade-seeking, while cooler conditions promote more sustained locomotion and foraging. Seasonal weather shifts also affect forage availability and the energetic demands of thermoregulation, thereby shaping daily time budgets and spatial strategies (Murphy, 2019; Marliani et al., 2021). Recognizing weather as a key driver of both spatial and temporal behavior provides essential context for interpreting patterns observed under domestic management and for providing resources needed to mitigate weather-related threats to equine well-being.

**Spatial Behavior in Horses**

Spatial behavior refers to how horses interact with their physical environment, including movement, navigation, and the use of space, and it plays a central role in equine welfare (Waring, 2003; Mellor, 2017). The organization of movement across a landscape determines how effectively horses access essential resources such as forage, water, shelter, and social contact (Hampson et al., 2010; Raizman et al., 2013; Rivero et al., 2021). Spatial freedom supports both physical health and psychological well-being by allowing horses to express natural foraging, locomotor, and social behaviors (Maisonpierre et al., 2019; Mellor, 2017).

Feral and semi-feral populations demonstrate the importance of spatial freedom for welfare. Australian brumbies (Hampson et al., 2010), Iberian horses (Miraglia et al., 2008), and North American mustangs (Hampson et al., 2010) travel between 5 and 28 km daily, depending on habitat complexity and resource distribution. Horses organize their space use around essential resources such as water and mineral licks, often establishing home ranges that span several square kilometers (Raizman et al., 2013; Rivero et al., 2021). Environmental features—including vegetation cover, elevation, and terrain type—strongly influence space-use patterns, with horses favoring open, level ground for movement and resting (Rose-Meierhöfer et al., 2010). These natural movement patterns support energy balance, hoof health, and social cohesion, reinforcing their importance as welfare indicators.

Resource distribution plays a central role in shaping how horses use space. The location and availability of essential resources—including forage, water, shelter, and suitable resting or rolling areas—strongly influence daily movement and spatial organization. Horses typically structure their activity around these points, forming predictable travel routes and core-use areas that link them (Raizman et al., 2013; Rivero et al., 2021). When resources are widely dispersed, horses must travel longer distances to meet their nutritional and hydration needs, increasing locomotion and time spent in transit. Conversely, when food, water, and shelter are clustered in proximity, movement distances decrease, and activity becomes more localized. Understanding how resource distribution influences spatial behavior is essential for designing domestic environments that support natural movement patterns and prevent welfare problems related to inactivity or environmental monotony.

Social flexibility in space use is also critical. Horses continually adjust their spatial relationships within the group to maintain social stability and minimize conflict. The ability to regulate proximity to conspecifics, including approaching or distancing according to social rank, affiliative bonds, or reproductive status, helps sustain harmony and reduce stress in unmanaged groups (Feh, 1999; Torres Borda et al., 2023; Waring, 2003). Spatial tolerance and synchronized movement within herds reflect established hierarchies and affiliative relationships, where dominant individuals often lead, and subordinate horses maintain appropriate following distances (Feh, 1999; Waring, 2003; Torres Borda et al., 2023). These dynamic spacing patterns are essential for group cohesion, effective communication, and safety, illustrating how social and spatial behaviors are intertwined components of equine welfare.

Environmental productivity also shapes home-range size and travel distances. In areas with abundant and evenly distributed forage, ranges are smaller and more concentrated, whereas in arid or variable ecosystems, horses extend their ranges substantially to meet nutritional and hydration needs (Raizman et al., 2013; Rivero et al., 2021). In domestic contexts, management decisions, such as field size, resource layout, and turnout time, strongly affect horses' ability to express these same movement strategies.

Together, these ecological and social influences highlight the complexity of equine space use and the importance of designing managed environments that support spatial freedom. When horses are provided with opportunities for voluntary movement and choice, they can more fully engage with their environment, maintain social cohesion, and experience improved welfare outcomes.

**Temporal Activity Patterns in Horses**

Equine behavior is strongly influenced by temporal rhythms that regulate daily (circadian) and seasonal (circannual) activity. Like many mammals, horses exhibit endogenous 24-hour cycles that synchronize with external cues such as light, temperature, and feeding schedules (Murphy, 2019; Hall & Kay, 2024a). These rhythms structure daily time budgets, balancing grazing, resting, locomotion, and social interactions. Time budgets typically follow a bimodal grazing pattern, with peaks during the morning and evening and reduced activity during midday and nighttime, when resting predominates (Marliani et al., 2021; Miraglia et al., 2008).

In addition to circadian cycles, horses exhibit circannual rhythms that regulate seasonal changes in physiology and behavior. Photoperiod is a primary environmental cue influencing circadian and circannual rhythms in horses, shaping coat growth, reproductive cycles, and overall activity budgets (Murphy, 2019). Mares are seasonally polyestrous, long-day breeders, with regular ovulatory estrous cycles occurring primarily during spring and summer as day length increases. Increasing photoperiod reduces nocturnal melatonin secretion, which stimulates hypothalamic gonadotropin-releasing hormone (GnRH) release and subsequent luteinizing hormone (LH) activity, leading to the resumption of cyclic ovarian function (Aurich, 2011).

Seasonal reproductive status may also influence temporal patterns of behavior, as estrous mares can exhibit increased locomotion, social interest, and responsiveness compared to luteal-phase or anovulatory periods. These hormonally mediated changes occur alongside seasonal shifts in daylight exposure and ambient temperature, suggesting that photoperiod-driven endocrine rhythms contribute to broader patterns of daily and seasonal activity expression. While the present study did not explicitly quantify reproductive state, acknowledging seasonal reproductive physiology provides important biological context for interpreting temporal variation in movement and activity measured via GPS tracking (Aurich, 2011; Murphy, 2019).

Management conditions can modify or disrupt these temporal rhythms. Fixed feeding schedules can entrain circadian cycles and provoke anticipatory activity (Seabra et al., 2023a; Irvine & Alexander, 1994), while limited turnout alters activity distributions and compresses natural movement patterns (Maisonpierre et al., 2019). Artificial lighting further disrupts circadian regulation, as erratic exposure fails to mimic natural photo periods and can alter physiological timing (Murphy, 2019). Together, these factors illustrate how domestic management can shift or constrain intrinsic biological rhythms.

The timing and structure of equine activity are also shaped by external environmental and management factors. Variables such as weather conditions, resource distribution, pasture size, group dynamics, and human-imposed schedules can significantly influence when and how horses engage in movement and rest (Rivero et al., 2021; Marliani et al., 2021). These influences can reinforce or disrupt the natural circadian and circannual rhythms of horses, underscoring the importance of considering both intrinsic biological cycles and external conditions when evaluating temporal activity patterns.

**Environmental and Management Factors Influencing Movement**

Understanding patterns of spatial organization is critical for designing management systems that accommodate the behavioral needs of domestic horses (Waring, 2003; Mellor, 2017). Restrictive environments that fail to provide sufficient voluntary movement and which limit opportunities to move freely between diverse resources disrupt natural movement strategies and can negatively affect welfare (Maisonpierre et al., 2019; Mellor, 2017). Acknowledging the spatial flexibility and adaptive movement strategies observed in free-ranging, feral, and wild horses offer key insights for promoting healthier, more behaviorally enriched domestic environments (Waring, 2003).

Field size and configuration are among the most influential factors shaping movement. Horses housed in small paddocks or stalls show substantially less locomotor activity than those with access to larger enclosures (McGowan et al., 2010; Rose-Meierhöfer et al., 2010). Larger fields provide greater opportunities for voluntary locomotion, exploration, and social interaction, with travel distances increasing logarithmically with enclosure size (Hampson et al., 2010). The design of enclosures, including their connectivity and access points, also affects movement by either constraining or facilitating the natural inclination to patrol and explore space.

In feral populations, widely dispersed water and grazing patches necessitate longer, more evenly distributed travel bouts throughout the daily cycle, whereas spatially concentrated resources in managed environments may compress movement into shorter, more predictable periods (Hampson et al., 2010; Raizman et al., 2013). Hay, water, and shelter are typically clustered within enclosures, resulting in localized activity and reduced overall movement demands (Rose-Meierhöfer et al., 2010; Maisonpierre et al., 2019). Feeding strategies that employ multiple hay nets or widely spaced foraging stations increase locomotion and promote more natural space-use patterns (McGowan et al., 2010). Similarly, rotational grazing systems can reintroduce variability in forage distribution, encouraging horses to move more within confined environments (Rose-Meierhöfer et al., 2010).

Terrain and topography also influence movement under managed conditions. While horses naturally prefer flatter, open ground for locomotion and resting (Rose-Meierhöfer et al., 2010), the design of domestic enclosures can either limit or encourage these preferences. Paddocks with uneven ground, heavy vegetation, or difficult footing may reduce locomotion, whereas open, well-drained areas promote more consistent movement (Rivero et al., 2021). Management that accounts for topographic variation can therefore support healthier and more natural activity patterns.

Management practices also determine how weather and thermal stress shape movement. While free-ranging horses adjust activity around heat and cold by seeking shade or sheltered terrain (Marliani et al., 2021; Rivero et al., 2021), domestic horses are often provided with stabling, blankets, or indoor feeding areas during adverse weather (McGowan et al., 2010). These interventions alter natural activity budgets by reducing the need for locomotion in search of shelter or forage. In hot conditions, shade structures or access to barns allow horses to minimize heat stress without the extensive movement observed in wild populations (Marliani et al., 2021), whereas in cold, wet climates, stabling or rugging can suppress the natural adjustments in foraging and locomotion otherwise seen in unmanaged environments (McGowan et al., 2010).

Social grouping further shapes spatial behavior in domestic contexts. Group size, sex composition, and dominance relationships influence access to resources and movement decisions. In confined pastures, larger groups or imbalanced dominance hierarchies can intensify competition, displace subordinate horses, and increase locomotion as they avoid conflict (Hausberger et al., 2008; Torres Borda et al., 2023). Conversely, compatible groupings and adequate space per horse promote synchronized grazing, stable spacing patterns, and reduced aggressive displacement (Hall & Kay, 2024a). Stocking density is therefore a key management factor linking social dynamics with spatial behavior and welfare outcomes (Maisonpierre et al., 2019).

Collectively, these environmental and management factors demonstrate how enclosure design, resource layout, topography, weather accommodations, and social grouping shape the movement opportunities available to domestic horses. When environments restrict voluntary locomotion, horses face elevated risks of health problems, stereotypic behaviors, and diminished agency. Conversely, management systems that mimic the spatial and social affordances of natural settings promote welfare by supporting more diverse, flexible, and self-determined movement patterns.

## Weather and Equine Behavior

Weather and seasonal variation are major external drivers of equine spatial and temporal behavior. Temperature, precipitation, and daylight cycles influence activity budgets, movement distances, and social interactions, often in ways that directly impact welfare. High ambient temperatures reduce locomotor activity, as horses seek shade or shelter and shift foraging to cooler periods of the day (Marliani et al., 2021; Rivero et al., 2021 (cattle study, used here as a comparative model for grazing livestock)). Conversely, cold or wet conditions may depress overall activity levels or redirect movement toward sheltered areas, altering resource use and patterns of social cohesion (Rivero et al., 2021 (cattle study, used here as a comparative model for grazing livestock)). These behavioral adjustments represent adaptive strategies for thermoregulation, yet they also affect opportunities for voluntary exercise, social contact, and foraging, which are central to welfare.

Seasonal shifts in photoperiod further regulate circadian and circannual rhythms in horses. Research on equine chronobiology demonstrates that light–dark cycles entrain activity patterns, feeding behavior, and hormonal rhythms, with implications for both performance and welfare (Murphy, 2019; Piccione et al., 2008). Shorter daylight hours in winter are associated with reduced movement and altered activity cycles, while longer days in summer support extended grazing and more even activity distributions. Artificial lighting and fixed management schedules can override these natural rhythms, sometimes compressing or disrupting innate temporal organization (Seabra et al., 2023).

Precipitation and ground conditions also play a role in shaping equine behavior. Prolonged rainfall creates muddy pastures that can restrict locomotion, increase the risk of hoof problems, and reduce grazing efficiency, whereas snow or ice may limit access to forage or water and alter travel routes (Murphy, 2019; Marliani et al., 2021). In managed settings, horses may be stabled or provided with covered feeding areas during adverse weather, buffering some of these environmental impacts but simultaneously constraining natural behavior (Maisonpierre et al., 2019). These interactions highlight the importance of considering both direct and management-mediated effects of weather when interpreting movement data.

For domestic horses, understanding weather-driven behavior is critical not only for welfare but also for land management. Heavy rainfall can concentrate horses in sheltered or high-use areas, exacerbating soil compaction and pasture degradation (Hassan-Vásquez et al., 2022; Rivero et al., 2021 (cattle study, used here as a comparative model for grazing livestock)). Conversely, dry seasons may increase movement distances as horses seek out dispersed water or forage, amplifying wear on areas of land (Hampson et al., 2010). Recognizing how environmental conditions interact with management systems is therefore essential for designing strategies that promote horse welfare while sustaining pasture health.

Collectively, weather influences equine behavior through multiple, interconnected pathways: thermoregulation, time budgets, social organization, and land use. By accounting for these factors, researchers and managers can more accurately interpret movement patterns and implement practices that align with both the biological needs of horses and the sustainability of the environments they inhabit.

**Use of GPS Technology in Animal Behavior Studies**

Advances in technology have transformed the study of animal behavior, providing researchers with innovative tools to measure and understand movement patterns across space and time. Among these, Global Positioning System (GPS) tracking has emerged as a particularly valuable method for collecting high-resolution, continuous data (Tomkiewicz et al., 2010; Kays et al., 2015; Hampson et al., 2010). One of the key practical considerations in GPS research is the duration of monitoring, which varies widely depending on device type, fix interval, and battery capacity. In feral horse studies, collars have recorded movement for periods ranging from several weeks to nearly nine months (Hampson et al., 2010; Kays et al., 2015). In domestic settings, shorter deployments of days to weeks are common, though they can be extended considerably because animals are accessible for recharging or device replacement (Rose-Meierhöfer et al., 2010). These differences highlight how GPS technology enables long-term monitoring under managed conditions but can be constrained by technical limits in free-ranging populations.

While GPS expands opportunities for fine-scale movement research, it also comes with trade-offs. Location data alone do not reveal the specific behavior being performed. For example, a stationary GPS point could indicate resting, sleeping, grazing, or even mortality, and it may also result from device loss or malfunction (Maisonpierre et al., 2019; Rychlicki et al., 2020). Integrating GPS data with accelerometers, direct observations, or health indicators is therefore often necessary to accurately interpret behavioral states.

To make sense of these large datasets, researchers rely on spatial tools capable of extracting meaningful ecological patterns. Geographic Information Systems (GIS) platforms are commonly employed to map movement paths, visualize habitat use, and quantify variables such as home-range size, core areas, and site fidelity (Cagnacci et al., 2010; Urbano et al., 2010). By integrating GPS trajectories with environmental layers, researchers can examine how factors such as terrain, vegetation, or resource distribution influence movement decisions. In equine studies, these approaches have been used to evaluate grazing distribution in rangelands, assess the impact of paddock design on locomotion, and compare activity between different management systems (Hampson et al., 2010; Rose-Meierhöfer et al., 2010; Rivero et al., 2021).

One way to address the behavioral ambiguity of GPS data is to combine it with complementary tools. Accelerometers can distinguish between locomotor states such as walking, trotting, and galloping, or identify when an animal is lying down versus grazing, while heart rate monitors and thermoregulation sensors add physiological context (Maisonpierre et al., 2019; Rychlicki et al., 2020). These integrated approaches allow researchers to connect spatial movement with welfare-relevant states, such as energy expenditure, stress, or thermal load. In domestic horses, such multimodal monitoring has provided insights into how turnout conditions, resource availability, and weather shape not only where animals move but also how they interact with their environment.

Despite these advantages, GPS use also presents challenges. Collars or harnesses must be securely fitted to prevent discomfort or injury, and data quality can be compromised by lost fixes, satellite drift, or battery depletion. Processing large datasets requires careful filtering to remove spurious points and appropriate analytical methods to calculate distances, identify home ranges, or detect behavioral states (Urbano et al., 2010; Seidel et al., 2018). Nevertheless, the expanding availability of affordable consumer-grade devices has increased opportunities for applied equine studies in commercial and farm settings, creating new pathways for evidence-based management (Maisonpierre et al., 2019; Matsubara et al., 2024).

Collectively, GPS tracking represents a powerful tool for advancing equine welfare research. By providing continuous, objective measures of movement, it enables direct evaluation of how environmental and management factors shape horses' spatial and temporal behavior. This technology bridges the gap between theoretical welfare frameworks and practical husbandry by making movement patterns visible and quantifiable, thereby supporting management decisions that better align with horses' behavioral needs. For domestic horses, this capacity to quantify movement directly links environmental management decisions to measurable welfare outcomes.

### Gaps in the Literature and Relevance of This Study

Despite substantial advances in GPS tracking technology and behavioral monitoring methodologies, significant gaps remain in the equine movement and welfare literature. Much of the existing research has focused on feral or semi-feral populations under naturalistic conditions (Hampson et al., 2010; Raizman et al., 2013; Rivero et al., 2021), leaving the movement patterns of domestic horses in managed environments comparatively underexplored (Maisonpierre et al., 2019; Marliani et al., 2021; Kjellberg et al., 2024; Kirton et al., 2024). Few studies have systematically examined how management factors such as turnout schedules, field size, resource distribution, and weather interact to shape the daily distances traveled and spatial organization of domestic horses. Understanding movement within these real-world contexts is critical for improving welfare but remains poorly characterized.

Another notable gap lies in the integration of fine-scale temporal data with environmental and management variables. While circadian and seasonal trends in equine behavior have been documented (Murphy, 2019; Piccione et al., 2008), fewer studies have linked short-term fluctuations in movement such as hourly activity levels to specific influences like feeding times, turnout routines, or field conditions (Seabra et al., 2023; Rivero et al., 2021). Without this resolution, the nuanced effects of routine management practices on behavioral expression remain difficult to quantify.

Although consumer-grade GPS devices have increased the accessibility of tracking technologies, questions about their accuracy, validation, and reliability in equine-specific contexts persist (Matsubara et al., 2024; Thompson, 2017). Studies evaluating device performance under the unique conditions of horse behavior, including high-speed gaits, grazing postures, and varied terrain, are limited. Broader adoption of these tools requires further evaluation of their feasibility for welfare monitoring in applied contexts.

Finally, the reciprocal relationship between horses and their environments remains underexplored. Horses can degrade pasture health through overgrazing, trampling, and congregation around resources (Hassan-Vásquez et al., 2022; Rivero et al., 2021), yet few studies have explicitly linked these land-use consequences back to horse welfare, such as how diminished forage quality or muddy conditions alter movement opportunities and increase health risks.

This study begins to address these gaps by using consumer-grade GPS devices (Tractive®) to continuously monitor the movement patterns of horses housed at a private boarding facility. By systematically linking spatial and temporal activity data to environmental and management variables, including feeding schedules, field sizes, and weather, this research provides novel insights into the factors influencing how domestic horses utilize space and time under managed care. In doing so, the study also evaluates the potential of accessible GPS technologies for welfare assessment and contributes to efforts to refine behavioral monitoring methods in applied equine management. Ultimately, this work aims to inform best practices by promoting environments that align more closely with horses' natural movement patterns while sustaining the health of the land they inhabit.

## Methods

### Study Design

This study examined how field size, time of day, and weather conditions influenced movement distances in domestic horses at Overlake Farm, a private boarding facility in Bellevue, Washington. Seventeen horses wore Tractive® GPS trackers that recorded location every 5 minutes. Only data recorded when a horse was simultaneously wearing an active tracker and located inside a mapped turnout field were included in analyses. Data were collected continuously from January through December 2024. Analyses presented here focus on the period from 2 January through 30 April 2024. This interval was selected to reduce seasonal, physiological, and management-related variability that could confound the interpretation of locomotor patterns. In the Pacific Northwest, winter and early spring are characterized by limited pasture growth and minimal availability of browse, resulting in relatively stable forage conditions across turnout fields. Ambient temperatures during this period are moderate and less variable than later in the year, reducing the influence of thermal extremes on movement behavior.

Physiological and management factors were also comparatively consistent during this time. Mares are seasonally polyestrous long-day breeders and typically do not exhibit regular ovulatory estrous cycles until late spring, thereby limiting reproductive influences on activity patterns during the study period (Aurich, 2011). In addition, farm activity was relatively stable, as riding schedules were reduced during winter and early spring and increased later in the year. Together, these conditions limit extraneous sources of variation affecting horse locomotion, providing a more controlled context in which to assess the effects of field size and daily temporal patterns on movement. Seasonal influences on movement behavior will be examined in future analyses incorporating the full year of GPS data.

**Figure 1:** A horse wearing a Tractive® GPS tracker attached to a collar during turnout.

**Study Site**

Overlake Farm comprises multiple barns and turnout areas of varying size, terrain, and vegetation cover. For clarity, all turnout areas are referred to collectively as fields. Boundaries of each field were digitized in ArcGIS® using high-resolution Google Earth imagery and assigned unique field numbers. These polygons defined the spatial framework for assigning GPS data to specific fields and for calculating area (m²) for each field.

**Figure 2:** Satellite image of Overlake Farm showing numbered fields used in the study.
Note. Field boundaries were digitized in ArcGIS® from Google Earth imagery and correspond to the field numbers listed in Table 3. Fields include all turnout areas of varying size and type, from small pens to large pastures.

**Subjects**

Seventeen domestic horses of mixed breeds, ages, and sexes were tracked (Table 1). Ages ranged from 8 to 28 years ($M = 20.1 \pm 5.6$ years) and included both mares and geldings. Housing and turnout routines varied: a few horses were stabled overnight and turned out during the day, while most remained on 24-hour turnout in fields. Groupings and turnout assignments were determined by farm staff based on social compatibility and facility logistics and were not experimentally manipulated. The number of horses contributing GPS data varied across the January–April study period due to routine management factors, including temporary removal from the property, changes in turnout assignments, and periods when trackers were removed for charging. Because this study used a non-random convenience sample and horses were not consistently present across all dates or fields, movement distance was summarized as the average distance traveled by all horses present within a given field and time. Monthly analyses, therefore, reflect the subset of horses contributing valid GPS data during each month, and sample sizes varied accordingly (Table 1).

Field group size also differed by field type. Horses in small fields were kept singly or in pairs, whereas horses in the largest 30-acre field lived in a mixed-sex herd that typically included 15–20 individuals. However, the exact number fluctuated slightly over the course of the study as horses were added or removed from the group for riding, health, or management reasons.

Horses were provided with forage and feed consistent with typical management at the facility. The large-herd field received orchard-grass hay distributed in multiple piles twice daily between 8–9 AM and 4–5 PM. Horses in smaller fields received orchard-grass and alfalfa hay according to owner preference. Except for the large-herd field, most horses were also fed a pellet concentrate once or twice daily, as requested by owners. In addition, all horses had *ad libitum* access to grazing within their turnout areas when vegetation was available.

**Table 1:** Demographic information for the 17 horses tracked at Overlake Farm from January to April 2024.

| Name | Breed | Age (years) | Sex | Horses contributing GPS data (days) | Study Date Range |
|---|---|---|---|---|---|
| Athena | Azteca | 16 | Mare | 119 | Jan 3 – Apr 30 |
| Bodie | Quarter Horse | 8 | Gelding | 101 | Jan 20 – Apr 30 |
| Cisco | Welsh Pony | 28 | Gelding | 85 | Feb 5 – Apr 30 |
| Copper | Appaloosa | 22 | Mare | 61 | Feb 29 – Apr 30 |
| Dude | Thoroughbred × Quarter Horse | 19 | Gelding | 119 | Jan 2 – Apr 30 |
| Icy Money | American Saddlebred | 20 | Gelding | 119 | Jan 2 – Apr 30 |
| Joe | Thoroughbred | 26 | Gelding | 118 | Jan 2 – Apr 30 |
| Kota | Thoroughbred | 25 | Gelding | 95 | Jan 2 – Apr 28 |
| Libby | Tennessee Walker | 21 | Mare | 120 | Jan 2 – Apr 30 |
| Luna | Andalusian | 17 | Mare | 119 | Jan 2 – Apr 30 |
| OVL-Luna | Andalusian | 22 | Mare | 36 | Mar 25 – Apr 30 |
| Rain | Appaloosa | 22 | Mare | 36 | Feb 10 – Mar 16 |

| | | | | | |
|---|---|---|---|---|---|
| River | Arabian | 18 | Mare | 75 | Jan 2 – Mar 16 |
| Scout | Quarter Horse | 27 | Gelding | 118 | Jan 2 – Apr 30 |
| Surprise | Pinto | 17 | Mare | 82 | Feb 9 – Apr 30 |
| Tedd | Paint | 25 | Gelding | 118 | Jan 2 – Apr 30 |
| Wally | Thoroughbred | 28 | Gelding | 80 | Feb 9 – Apr 30 |

Note. Ages ranged from 8 to 28 years (M = 20.1, SD = 5.6).

**GPS Data Collection**

Each horse wore a Tractive® GPS tracker attached to a breakaway collar during turnout. Devices recorded latitude and longitude every 5 minutes. Raw data, including horse identity, device ID, coordinates, and timestamps, were downloaded from the Tractive® web platform in Coordinated Universal Time (UTC) and converted to Pacific Time (PT). Each GPS data point qualified for analysis only if the tracker was being worn and the location fell within a mapped field boundary. Across all horses, the raw dataset contained 720,346 GPS points, of which 710,311 (98.6%) met the inclusion criteria and were retained for analysis; 10,035 points (1.4%) were excluded because the tracker was not worn, charging, or produced out-of-bounds coordinates. Periods when horses were temporarily off the property or when GPS trackers were removed for charging were excluded from analysis. Although all horses had continuous access to covered shelters within their turnout areas, none were confined to stalls during the study period. GPS signal obstruction occasionally occurred when horses were positioned under shelter structures; data gaps associated with these periods were identified during data cleaning and excluded. After cleaning, the remaining valid GPS points were compiled in Excel® for subsequent spatial and statistical analyses.

**Table 2:** Number and percentage of GPS data points retained and removed per horse after data cleaning.

| Horse | Status | Data points | % of total for that horse |
|---|---|---|---|
| Athena | Keep | 57,380 | 98.31% |
| | Remove | 987 | 1.69% |
| Bodie | Keep | 46,538 | 98.98% |
| | Remove | 479 | 1.02% |
| Cisco | Keep | 35,882 | 98.07% |
| | Remove | 705 | 1.93% |
| Copper | Keep | 21,604 | 98.46% |
| | Remove | 337 | 1.54% |
| Dude | Keep | 58,585 | 99.77% |
| | Remove | 135 | 0.23% |
| Icy Money | Keep | 55,775 | 97.62% |
| | Remove | 1,357 | 2.38% |
| Joe | Keep | 55,222 | 98.71% |
| | Remove | 719 | 1.29% |
| Kota | Keep | 34,561 | 98.61% |
| | Remove | 486 | 1.39% |
| Libby | Keep | 54,903 | 98.71% |
| | Remove | 718 | 1.29% |
| Luna | Keep | 57,281 | 98.75% |

| | | | |
|---|---|---|---|
| | Remove | 727 | 1.25% |
| OVL-Luna | Keep | 16,000 | 97.87% |
| | Remove | 349 | 2.13% |
| Rain | Keep | 13,247 | 99.33% |
| | Remove | 90 | 0.67% |
| River | Keep | 33,185 | 98.81% |
| | Remove | 401 | 1.19% |
| Scout | Keep | 47,655 | 98.72% |
| | Remove | 618 | 1.28% |
| Surprise | Keep | 40,585 | 99.10% |
| | Remove | 369 | 0.90% |
| Tedd | Keep | 47,798 | 98.12% |
| | Remove | 918 | 1.88% |
| Wally | Keep | 34,110 | 98.16% |
| | Remove | 640 | 1.84% |
| Total | Keep | 710,311 | 98.61% |
| | Remove | 10,035 | 1.39% |
| | Grand Total | 720,346 | 100.00% |

Note. Data reflects the number of individual GPS records retained ('Keep') and excluded ('Remove') per horse after filtering and cleaning.

Battery life varies by tracker and charging routine. In general, most tracker batteries lasted 3–7 days, depending on signal conditions and individual use, and required 12–24 hours to recharge fully. Charging schedules differed among horses because owners and staff removed and recharged devices at varying intervals. Occasional gaps in the data occurred when a tracker was not recharged immediately after battery depletion; these gaps varied among individuals and reflected owner-managed charging schedules rather than any consistent pattern across the study population.

**Spatial Data Processing**

Digitized field polygons were imported into ArcGIS® for mapping and analysis. The geodesic area ($m^2$) of each polygon was calculated, and its numeric field ID was used to assign GPS points. Points falling outside any mapped turnout polygon failed the inclusion criteria and were excluded.

Each recorded GPS point was compared with the mapped field boundaries to assign it to the correct turnout area. This process ensured that every GPS record was linked to the correct field based on the horse's verified location. To account for GPS error and ensure biological accuracy: (1) daily management records from farm staff were used to confirm which field each horse occupied, allowing verification of GPS field assignments; (2) points falling slightly outside the boundary, but forming a continuous array or cloud immediately adjacent to the correct field perimeter, were retained in analyses for that horse as normal positional drift; and (3) points leading toward other parts of the farm, such as barns or arenas, were excluded as they reflected horses being led for training, riding, or care rather than free movement within the field.

Horses in the study occupied 30 of the 43 mapped fields (Table 3). Fields 12 and 13 were physically contiguous and allowed unrestricted horse movement; therefore, they were combined and analyzed as a single turnout area. Turnout assignments were not experimentally controlled but reflected the farm's normal management practices. Some horses remained in the same field throughout the study period, while others were periodically moved between fields depending on factors such as weather, grazing rotation, or social compatibility. The composition of groups within each field was therefore relatively stable but not fixed. Horses were generally turned out with familiar companions, although occasional changes occurred when individuals were reassigned to different fields. These natural management movements were recorded in the farm's daily logs and were used to verify GPS field assignments during data processing.

**Table 3:** Calculated area ($m^2$) of turnout fields occupied by tracked horses (January–April 2024)

| Field No. | Field Name | Area ($m^2$) |
|---|---|---|
| 16 | Pen | 76.79 |
| 15 | Pen | 95.12 |
| 28 | Pen | 100.15 |
| 42 | Pen | 110.92 |
| 39 | Pen | 116.32 |
| 41 | Pen | 122.06 |
| 8 | Pen | 123.55 |
| 26 | Pen | 137.54 |
| 40 | Pen | 138.60 |
| 29 | Pen | 156.81 |
| 19 | Pen | 176.96 |
| 21 | Paddock | 207.17 |
| 4 | Paddock | 342.06 |

| | | |
|---|---|---|
| 3 | Paddock | 343.43 |
| 24 | Paddock | 425.50 |
| 2 | Paddock | 477.02 |
| 23 | Small Pasture | 975.73 |
| 32 | Small Pasture | 1,470.41 |
| 25 | Small Pasture | 1,774.41 |
| 22 | Small Pasture | 1,925.29 |
| 33 | Small Pasture | 2,829.85 |
| 5 | Small Pasture | 3,034.08 |
| 35 | Small Pasture | 3,085.96 |
| 34 | Large Pasture | 5,068.45 |
| 10 | Large Pasture | 5,455.69 |
| 1 | Large Pasture | 5,476.05 |
| 11 | Large Pasture | 6,322.66 |
| 36 | Large Pasture | 6,494.38 |
| 12 & 13 | Large Field | 124,788.90 |

Note. Field areas were calculated in ArcGIS using geodesic area measurements based on digitized polygon boundaries.

**Distance and Time Calculations**

Distances were computed using the spherical law of cosines, which provides results equivalent to the Haversine formula at the spatial scale of this study. The difference between the two methods is less than one millimeter for distances under one kilometer, and therefore negligible for within-field movement analyses.

The formula is:

$$d=R\cdot\arccos(\sin(\phi\_1)\sin(\phi\_2)+\cos(\phi\_1)\cos(\phi\_2)\cos(\Delta\lambda))$$

In this equation, d represents the great-circle distance between two points on the Earth's surface, and R is the Earth's radius, set at 6,371 km. The variables $\varphi_1$ and $\varphi_2$ denote the latitudes of the two points (in radians), while $\Delta\lambda$ represents the difference in their longitudes. The formula calculates distance as the product of the Earth's radius and the arccosine of the sum of the products of the sines and cosines of the two latitudes and the cosine of the longitudinal difference.

For each horse, the following metrics were derived:

- Total distance traveled (km): sum of all valid inter-fix distances.

- Average distance per GPS-tracked day (km/day): total distance divided by the number of days with valid GPS records.

- Average distance per calendar day (km/day): total distance divided by the total number of calendar days between the first and last record.

To examine temporal patterns, data were binned into four 6-hour time blocks: (1) night (0000–0600 h), (2) morning (0600–1200 h), (3) afternoon (1200–1800 h), and (4) evening (1800–0000 h). These intervals correspond to natural circadian cycles and daily routines (Table 3) (Murphy, 2019). Distance traveled within each interval was summed per horse per day for repeated-measures analysis.

## Weather Data Integration

Weather data (temperature °C, precipitation mm, dew point °C, and wind speed km/h) were obtained from the nearest reporting station on wunderground.com for the full study period. Each GPS point was matched by date and time to the corresponding weather observations.

## Statistical Analyses

All statistical analyses were performed in IBM SPSS Statistics (Version 29). Before analysis, GPS data were screened for missing values, outliers, and implausible positional jumps greater than 200 m within a 5-minute interval. Valid data were aggregated by horse, field, and 6-hour time block.

Relationships between field size and daily distance traveled were examined using correlation and regression analyses. A repeated-measures analysis of variance (ANOVA) was conducted to compare movement across four daily time intervals (night, morning, afternoon, and evening). Weather variables, including temperature, precipitation, and dew point, were evaluated as potential predictors of movement using multiple linear regression models. Effect sizes ($\eta^2$ and Cohen's d) were calculated for all primary analyses, and statistical significance was set at $p < .05$.

# Results

## Dataset Overview

GPS tracking was conducted from January through April 2024 across 29 turnout fields at Overlake Farm. Seventeen horses contributed movement data, yielding 472 six-hour time-block observations (118 days × 4 time blocks per day). Horses were rotated among turnout areas according to routine management needs; some horses and some fields contributed more data than others. This variation reflects natural differences in turnout scheduling and field availability rather than a controlled experimental design.

**Field Size Descriptive Statistics**

Field areas ranged from 76.79 m² (small holding pens) to 124,788.90 m² (the 30-acre field). Across all turnout conditions, the mean daily distance traveled was 12.05 km (SD = 7.47). Horses in larger turnout areas traveled greater distances per day than those in smaller areas. Figure 1 shows the field-level scatterplot (N = 29) on a logarithmic scale. The correlation between log-transformed field size and mean daily distance traveled was moderate ($r \approx .34$), indicating that while larger areas generally supported more movement, considerable variability existed within categories.

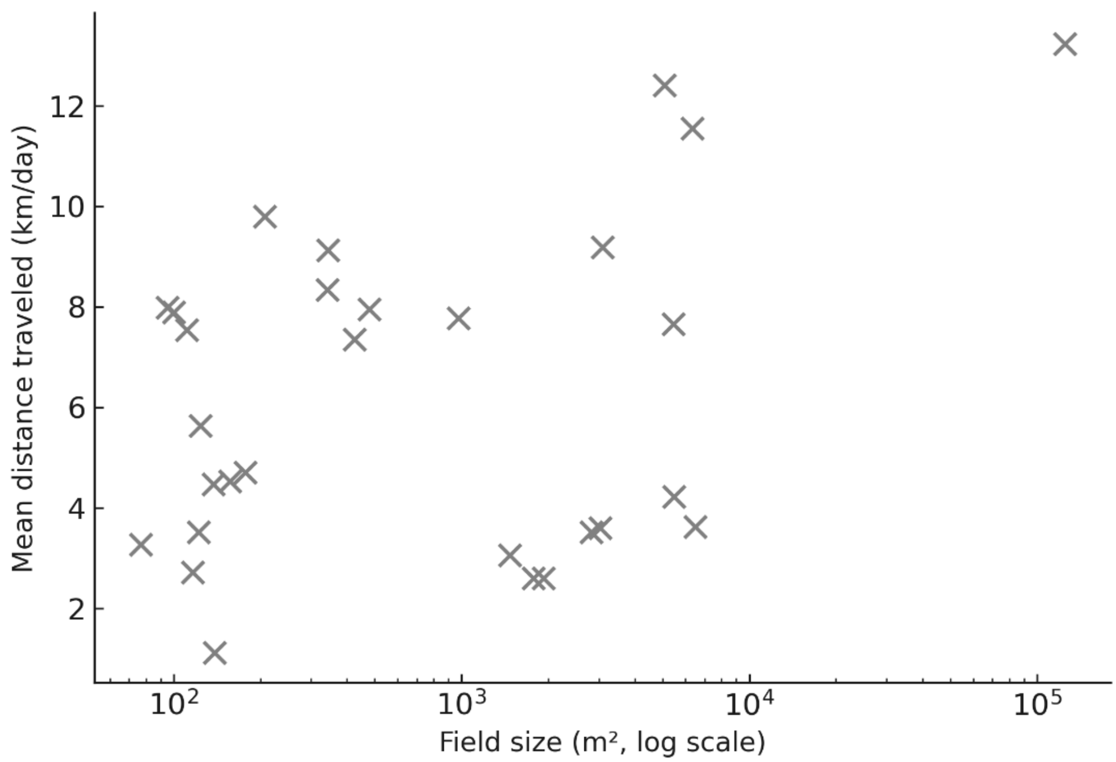

**Figure 1: Field-level relationship between field size and daily distance**. Scatterplot showing the relationship between field size and mean daily distance traveled over 118 days of the study. Each point represents one turnout area (N = 29). Field size is displayed on a logarithmic scale to accommodate the wide range in area. Larger fields were associated with greater daily distance traveled, although variability within categories suggests that additional factors also contributed to movement.

To examine scaling effects, turnout fields were grouped into five size categories based on area: pens (< 200 $m^2$), paddocks (200–< 500 $m^2$), small pastures (500–< 4,000 $m^2$), large pastures (4,000–< 20,000 $m^2$), and a large field (≥ 20,000 $m^2$). Log-transformed field area values were used in correlation and regression models to evaluate the nonlinear relationship between field size and distance moved. Mean daily distances increased steeply up to approximately 20,000 $m^2$ (~5 acres) and then leveled off in the largest areas (Figure 2).

**Table 4:** N, Mean area ($m^2$), and SD for each field group.

| **Field group** | **N** | **Mean area ($m^2$)** | **SD ($m^2$)** |
|---|---|---|---|
| Pen | 11 | 123.17 | 28.52 |
| Paddock | 5 | 359.04 | 102.39 |
| Small pasture | 7 | 2,156.53 | 831.85 |
| Large pasture | 5 | 5,763.45 | 613.86 |
| Large field | 1 | 124,788.90 | — |

Note. SD isn't applicable for the large field group because N = 1. Also, Fields 12 and 13 were combined into one turnout unit (124,788.90 $m^2$) because horses had unrestricted movement between them.

Daily distance traveled increased sharply from the smallest to mid-range turnout categories. Horses in pens traveled the least (approximately 5 km/day), followed by a substantial increase in paddocks (~8 km/day). Movement continued to rise in small pastures (~10–11 km/day) and increased more modestly in large pastures (~12–13 km/day). Horses in the largest field traveled the farthest, approximately 15 km/day.

Mean daily distance traveled across these categories followed a logarithmic, asymptotic pattern, with steep increases in movement from very small areas up to roughly 20,000 $m^2$ (~5 acres) and a clear plateau thereafter (see Figure 2). This diminishing-returns pattern indicates that while increasing space initially yields sizable gains in locomotion, additional acreage beyond moderate pasture size contributes relatively little to further increasing daily movement. This result is consistent with Hampson et al. (2010), who documented similar asymptotic increases in movement among Australian feral horses as paddock size expanded beyond minimal spatial thresholds.

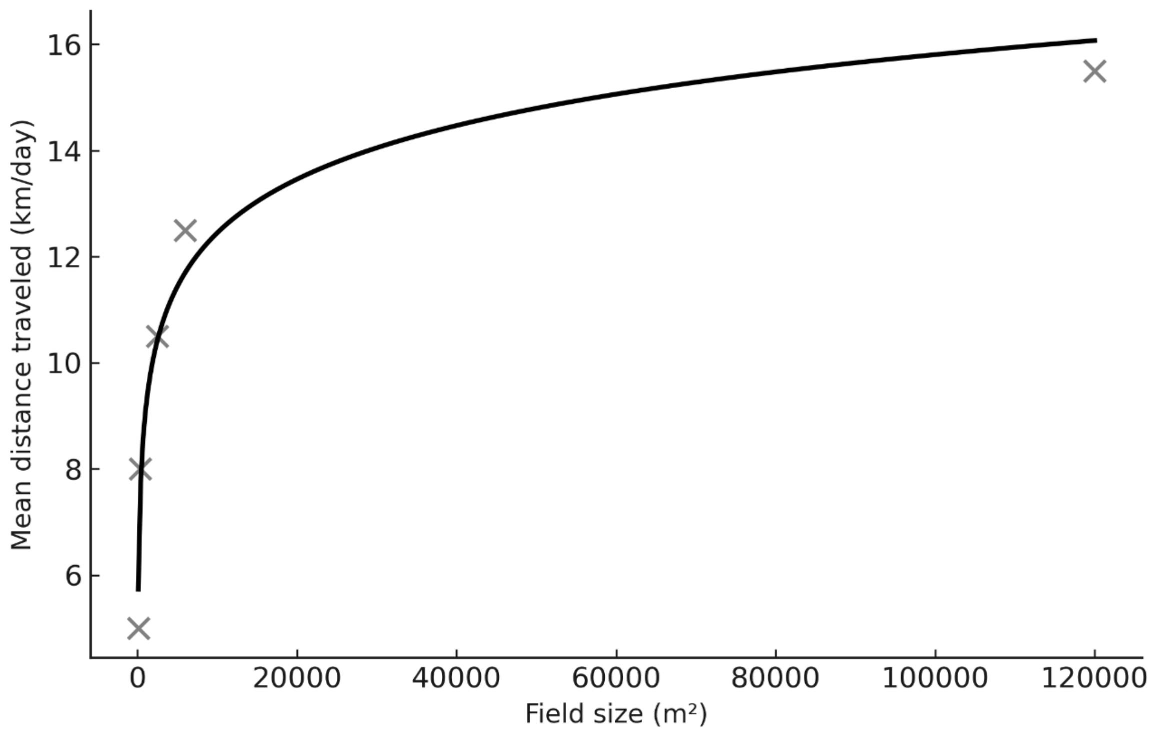


**Figure 2: Relationship between field size and daily distance traveled**. Logarithmic relationship between turnout field size and mean daily distance traveled by domestic horses. Scatter points represent mean daily distance traveled within each turnout area category (pens ≈ 5 km/day, paddocks ≈ 8 km/day, small pastures ≈ 10–11 km/day, large pastures ≈ 12–13 km/day, and the large field ≈ 15 km/day). The fitted logarithmic curve illustrates steep increases in movement from very small turnout spaces up to approximately 20,000 m², followed by a plateau in the largest fields, indicating diminishing gains in locomotion as available space expands.

## Time-of-Day Descriptive Statistics

Each 24-hour day was divided into four 6-hour periods: night (0000–0600), morning (0600–1200), afternoon (1200–1800), and evening (1800–2400). Horses traveled the farthest during the afternoon (M = 13.99 km, SD = 1.87) and morning (M = 13.72 km, SD = 1.54), followed by evening (M = 12.15 km, SD = 1.44), and least during the night (M = 11.60 km, SD = 1.23; see Figure 3). These descriptive differences suggest a possible diurnal activity pattern.

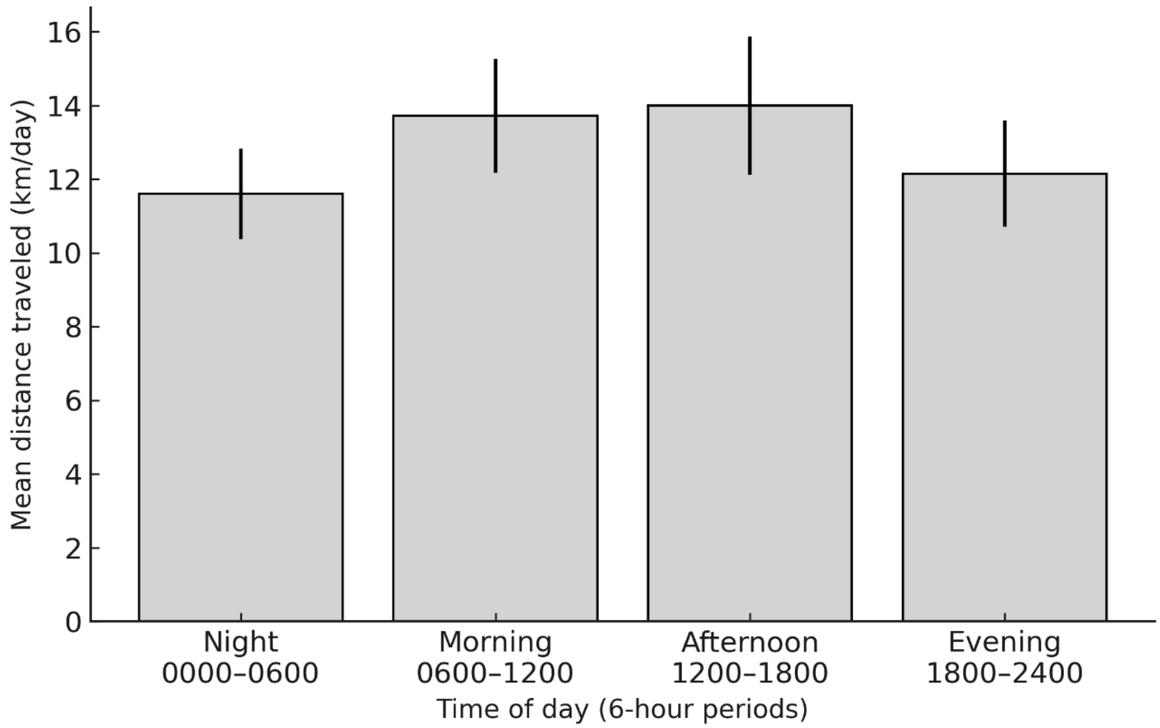


**Figure 3: Mean distance traveled by time of day (January-April 2024)**. Mean distance traveled by domestic horses across four 6-hour time periods (January–April 2024). Bars show the mean distance traveled during each time block, with error bars representing standard deviations. Horses traveled the farthest during the morning and afternoon periods and the least during the night, illustrating a clear diurnal activity pattern consistent with circadian behavioral rhythms.

A one-way ANOVA tested whether distance traveled differed across the four time-of-day periods. There was a significant effect of time of day, $F(3, 468) = 68.52$, $p < .001$, $\eta^2 = .31$. Post hoc comparisons showed that distances traveled during the morning and afternoon were significantly greater than those during the evening and night (all $p < .001$). In contrast, morning and afternoon distances did not differ significantly ($p = .524$), while a small but significant difference was observed between evening and night ($p = .032$).

To evaluate whether the diurnal pattern persisted when field size was held constant, an analysis was conducted using data from the two largest fields (Fields 11 and 12/13; N = 17 horses). A repeated-measures general linear model again showed a significant effect of time of day, Pillai's Trace = .79, $F(3, 14) = 17.49$, $p < .001$, $\eta^2 = .79$. Thus, horses exhibited robust diurnal movement patterns even under conditions with minimal spatial restriction.

**Weather Descriptive Statistics**

Variation in daily weather conditions was modest across the study period (January–April 2024), characteristic of the late-winter and early-spring climate in the Pacific Northwest. Summary descriptive statistics for all weather variables, i.e., temperature, precipitation, and dew point, are presented in Table 1.

**Table 1:**

*Descriptive statistics for daily weather variables per 6-hour period recorded at Overlake Farm from January through April 2024.*

| Weather variable | Minimum | Maximum | Mean (M) | Standard deviation (SD) |
|---|---|---|---|---|
| Temperature (°C) | -8.89 | 23.33 | 9.01 | 4.63 |
| Dew point (°C) | -19.44 | 12.78 | 3.41 | 4.83 |
| Precipitation (mm) | 0 | 5.08 | 0.28 | 0.83 |

Movement increased modestly with higher temperatures, and temperature was significantly positively correlated with distance traveled. The fitted regression line illustrates a modest but statistically significant positive association between warmer temperatures and greater movement ($r = .17$, $p < .001$). Each 1°C increase in maximum temperature was associated with an increase of approximately 0.04 km in distance traveled per 6-hour period. (Figure 4)

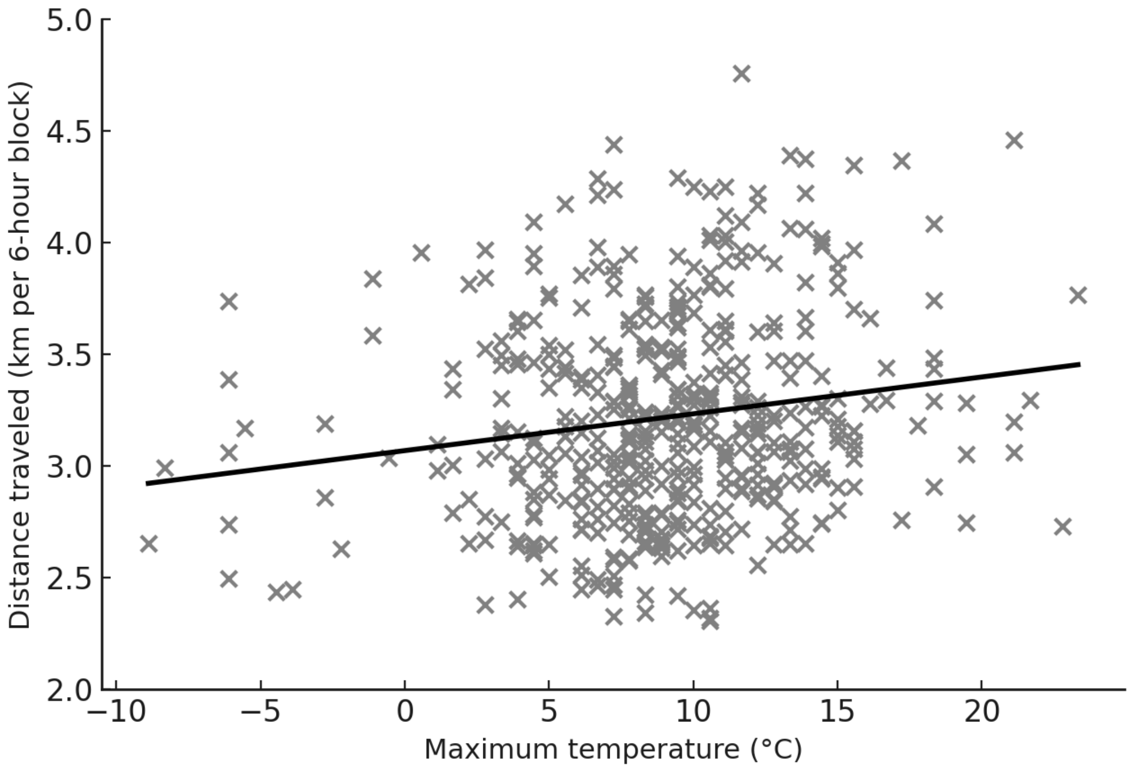


**Figure 4: Relationship between temperature and distance traveled**. Relationship between maximum temperature and average distance traveled per 6-hour period.

**Monthly Descriptive Statistics**

Mean daily movement decreased across the four months. Horses traveled the least distance in April (M = 11.87 km, SD = 1.01) compared with January (M = 13.45 km, SD = 1.88), February (M = 12.94 km, SD = 1.88), and March (M = 13.23 km, SD = 2.02). A one-way ANOVA indicated a significant effect of month on distance traveled, $F(3, 471) = 19.18$, $p < .001$, $\eta^2 = .11$. Post hoc comparisons showed that April distances were significantly lower than those in January, February, and March (all $p < .001$). The first three months did not differ significantly from one another.

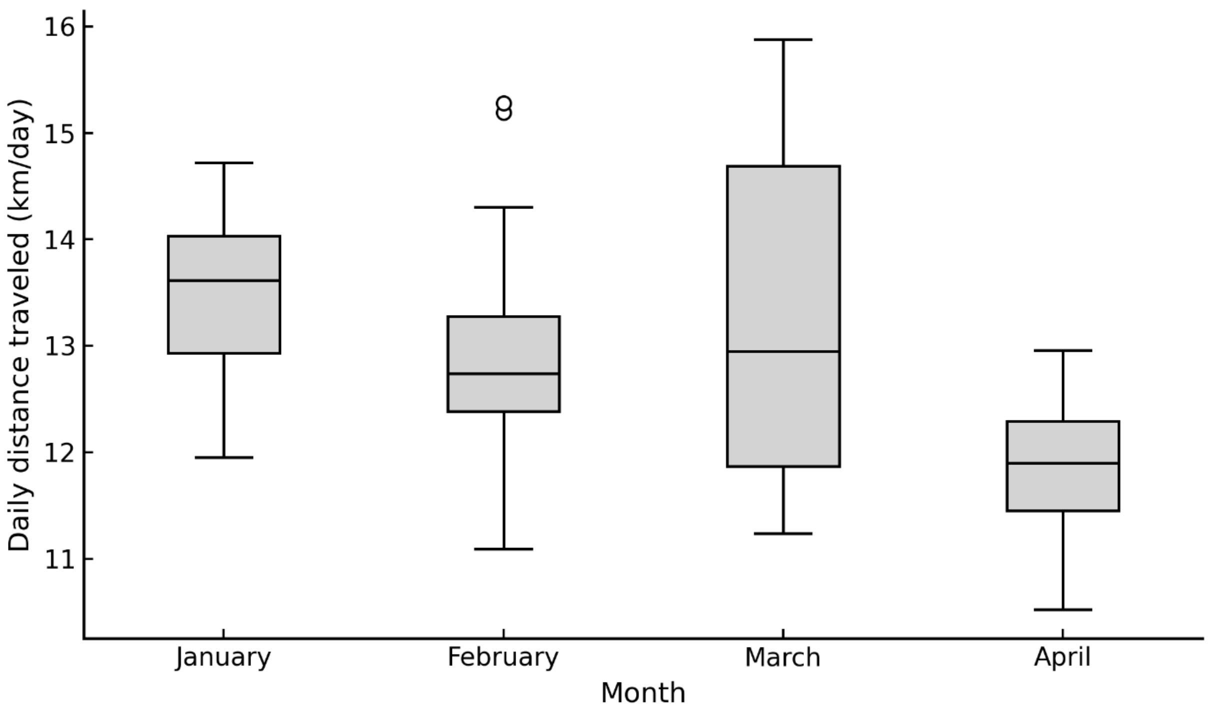


**Figure 5: Distribution of average daily distance traveled for each month from January to April 2024**. Daily distance was calculated as the sum of four 6-hour movement periods per day. Boxes represent interquartile ranges, horizontal lines indicate medians, and whiskers represent 1.5 × IQR.

During this same period, average maximum temperatures increased across months, from January ($M = 6.14$°C, $SD = 5.68$) to April ($M = 12.13$°C, $SD = 3.48$). A one-way ANOVA revealed that monthly differences in movement were statistically significant, $F(3, 468) = 19.18$, $p < .001$, $\eta^2 = .11$.

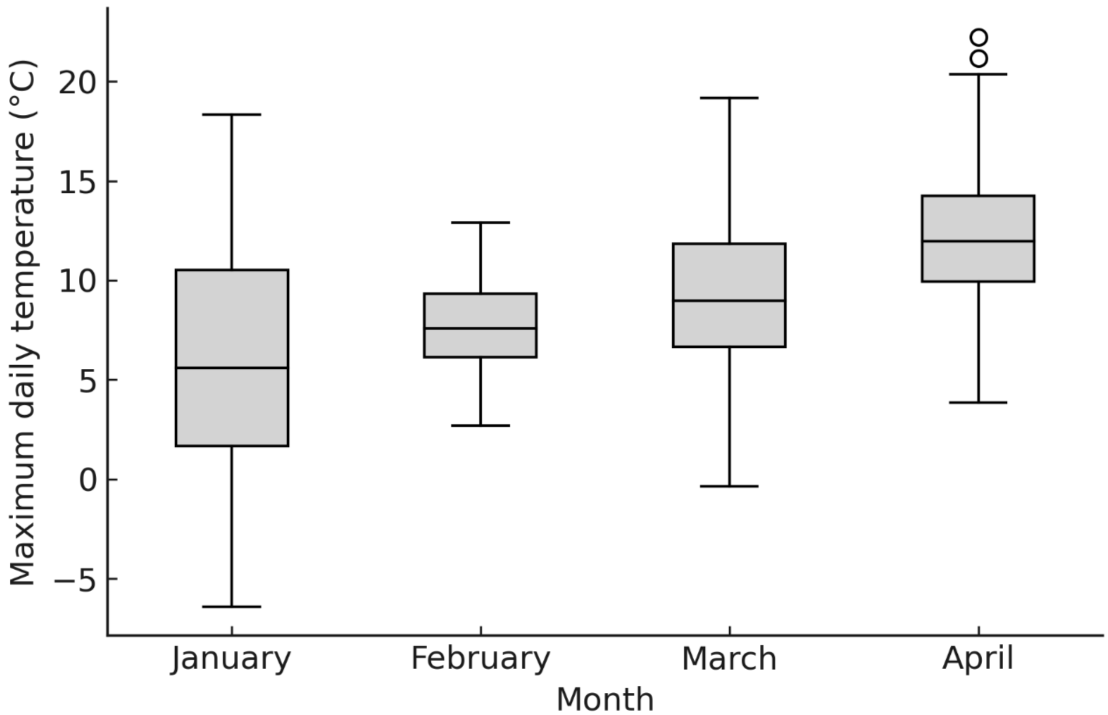


**Figure 6: Distribution of maximum daily temperature (°C) for each month from January to April 2024**. Each box represents the interquartile range, with medians marked by horizontal lines and whiskers depicting the range of non-outlier values. As expected seasonally, temperatures were lowest in January (M = 6.14°C) and increased steadily each month through April (M = 12.13°C). Monthly differences in maximum daily temperature were statistically significant, $F(3, 468) = 47.47$, $p < .001$, and each consecutive month was significantly warmer (add stats for the post hoc comparison for monthly temperatures).

To examine the extent to which month, time of day, and weather variables predicted distance traveled, a backward multiple regression was conducted with month, time-of-day block, temperature, dew point, and precipitation entered in the initial model. Backward elimination removed precipitation ($p = .978$), time-of-day block ($p = .388$), and dew point ($p = .184$). The final model retained month and temperature as significant predictors of horse movement distance, $F(2, 469) = 54.50$, $p < .001$, $R^2 = .19$.

## Discussion

The present study examined how domestic horses use space under typical farm management by analyzing four months of GPS-tracked movement across a broad range of field sizes. Three major findings emerged. First, daily locomotion was strongly shaped by the size of the turnout field, with substantial differences between very small enclosures and moderately sized pastures. Second, horses displayed robust circadian patterns of movement, traveling the greatest distances during daylight hours, particularly in the afternoon, and the least at night. Third, temperature contributed significantly to variation in movement, with horses traveling greater distances as ambient temperature increased. Despite the limited range of temperatures observed during the winter months, this effect was statistically significant, suggesting that horses may be highly sensitive to relatively small thermal fluctuations when operating near lower thermal thresholds. Together, these results clarify how spatial, environmental, and management conditions interact to structure the daily movement patterns of domestic horses.

### Field Size Effects on Movement

Field size exerted the strongest influence on locomotion. Horses housed in small pens and paddocks traveled markedly shorter distances than those in pastures or larger turnout areas, consistent with previous GPS-based work demonstrating that spatial restriction is one of the primary determinants of equine movement (Hampson et al., 2010; Kirton et al., 2024; Kjellberg et al., 2024). Similar relationships have been documented in studies of restricted grazing systems and active open-barn environments, where increasing accessible area enhances overall locomotor activity and allows horses to express more naturalistic behavioral repertoires (Kirton et al., 2024; Kjellberg et al., 2024; Seabra et al., 2023).

Movement in the present study increased sharply when horses transitioned from small enclosures to moderately sized pastures. Beyond approximately 20,000 m² (about 5 acres), further increases in acreage yielded diminishing returns, with daily travel distances plateauing even as field size continued to expand. This logarithmic pattern mirrors findings in both domestic and free-ranging horses, where distance moved rises steeply until basic spatial thresholds are met and stabilizes once horses have adequate room for continuous walking and exploration (Hampson et al., 2010).

While gait type was not quantitatively analyzed, anecdotal differences across fields were consistent with established welfare science. Horses in very small areas showed short, repetitive movements along fence lines and, in some cases, did not have enough room to canter or gallop, whereas horses in larger areas displayed longer routes and a wider range of gaits. These observations align with research demonstrating that ample space allows horses to engage in species-typical locomotor behaviors and reduces repetitive or frustration-driven movement (Mellor, 2017; Hall & Kay, 2024). Agricultural extension principles also emphasize that adequate turnout area supports both equine welfare and pasture sustainability. Although these recommendations typically focus on forage capacity, they inherently reflect minimum space allowances required for normal movement. In regions with wet, fragile soils, such as western Washington, conservative stocking densities are necessary to maintain pasture health, indirectly reinforcing the spatial requirements highlighted here.

Collectively, these results demonstrate that field size is a central determinant of both the quantity and quality of equine movement. Providing horses with sufficient space enables more diverse and natural locomotor patterns, supports behavioral health, and aligns with welfare frameworks that emphasize opportunities for positive agency and expression of natural behaviors (Mellor & Beausoleil, 2015; Mellor, 2017).

**Circadian Patterns of Daily Movement**

Daily movement followed a clear diurnal rhythm; horses traveled farthest during the morning and afternoon and least during nighttime hours. These results are consistent with prior findings that both domestic and free-ranging horses concentrate foraging and walking during daylight periods and reduce, but do not eliminate, movement at night (Miraglia et al., 2008; Maisonpierre et al., 2019; Seabra et al., 2023). Such rhythms reflect fundamental aspects of equine chronobiology, in which light–dark cycles act as primary zeitgebers regulating behavioral and physiological processes (Murphy, 2019). At the same time, horses exhibit sensory and sleep-related adaptations that support activity under low-light conditions, including highly sensitive scotopic vision and a reduced requirement for recumbent sleep, averaging approximately 60 minutes per day. These traits reflect their evolutionary history as prey animals, allowing flexibility in activity timing while maintaining vigilance and responsiveness across the 24-hour cycle (Waring, 2003; McDonnell, 2003).

Management practices likely also interacted with these endogenous rhythms. Horses at Overlake Farm were fed in the morning and afternoon, and movement often increased in anticipation of staff presence during those times. Anticipatory behavior around predictable feeding events, including increased locomotion, vigilance, and orientation toward human activity, is well documented in domestic horses (Hausberger et al., 2008; Hall & Kay, 2024). The greater morning and afternoon activity observed in this study likely reflect this interaction between intrinsic circadian patterns and routine management cues.

Recognizing this interplay has practical welfare implications. Domestic horses possess strong behavioral rhythms shaped by near-continuous foraging and stable social contact with conspecifics (Waring, 2003; McDonnell, 2003), yet structured human management schedules may concentrate activity into narrower temporal windows that differ from species-typical patterns. Adjusting feeding routines, distributing forage more evenly across the day and throughout the enclosure, and implementing slow-feeding systems may help align management practices with horses' natural temporal patterns, reducing the intensity of anticipatory arousal and supporting more stable daily rhythms, including locomotory activity.

### Weather Influences on Movement

Weather contributed relatively little variation in movement during the study period. Maximum daily temperature had a small yet statistically significant effect on the distance traveled by horses. Dew point and precipitation showed simple correlations with movement but did not predict movement once other variables were taken into account, suggesting that their bivariate associations reflected shared variance rather than independent influence.

These findings likely reflect the mild, relatively stable winter-to-spring conditions during data collection. Substantial weather-driven variation in equine behavior, including locomotion, typically arises under more extreme environmental conditions. Elevated temperatures are commonly associated with reduced movement and increased standing or resting behavior as horses mitigate heat stress, whereas colder conditions can similarly suppress locomotion due to increased energetic demands and the need for thermal conservation (Maisonpierre et al., 2019; Seabra et al., 2023). Given the absence of severe heat, cold, or rainfall in this dataset, temperature-related changes in movement were modest, and spatial factors remained far more influential predictors of daily locomotion.

**Monthly Patterns and Land Stewardship Implications**

Movement distance was consistent from January through March but declined in April, which was also the warmest month. In general distance moved increased with temperature, so this finding was somewhat unexpected. One possible explanation relates to seasonal management practices that begin in April. Early spring, with higher temperatures and reliable rainfall, is when fields are seeded, and new grass begins to grow. Horse movement distance might be affected in two ways. First, horses vulnerable to laminitis are typically moved from larger pastures with new grass growth to smaller paddocks and sacrifice areas. Second, routine spring pasture management restricts horses' access to larger fields and pasture rotation to protect early grass growth and to conduct reseeding and pasture recovery. In addition, horses at metabolic risk, including those prone to laminitis, have restricted access to high non-structural carbohydrate (NSC) spring forage. One possible explanation for the observed decline in movement in April is reduced availability of turnout space, which may have constrained locomotor opportunities. However, because field assignments were not systematically examined across months, this interpretation should be treated cautiously and cannot be distinguished from other unmeasured management or seasonal factors. These potential management-driven changes demonstrate how routine seasonal practices can temporarily constrain movement independent of environmental conditions. Additional exploration of this data is needed to explore this hypothesis.

These results hold practical implications for designing turnout systems that support both equine welfare and sustainable land use. Very small enclosures impose significant movement restrictions, emphasizing the importance of providing horses with access to adequate space whenever possible. Moderately sized pastures (approximately 2–5 acres) in this study supported daily travel distances approaching those reported for free-ranging horses in prior research

(Hampson et al., 2010; Miraglia et al., 2008). Such fields may therefore strike a balance between providing sufficient locomotor opportunity while maintaining manageable rotational grazing systems, where horses are rotated among paddocks to allow forage regrowth and recovery. This approach supports pasture persistence by reducing localized overgrazing, maintaining vegetative cover, and distributing hoof impact more evenly across the landscape, while still permitting meaningful daily movement (Noble, 2023).

Integrating horses' daily activity patterns may help reduce pasture overuse during vulnerable periods, particularly in wet climates. Distributed feeding strategies, in which forage is provided across both space and time rather than concentrated into single feeding events, may help align management practices with horses' natural foraging rhythms (Noble, 2023; Seabra et al., 2023). To support precision land management, multiple horses could be tracked concurrently, as was done in this study, providing data for proximity and co-occurrence analyses to identify hotspots of field wear.

**Limitations and Future Directions**

Several limitations warrant consideration. The study employed a convenience sample, measuring distance moved by any horses that were fitted with trackers. Consequently, the number and identity of about half of the participating horses changed over the study period. In addition, horses were not randomly assigned to turnout fields, making it difficult to separate individual differences from the effect of field size. Within-horse comparison of sensitivity to spatial restriction, which would strengthen causal inference could be made on horses in this study that changed fields during the year.

GPS receivers inevitably introduce positional errors, and measurement uncertainty can systematically inflate recorded distances; however, such error was consistent across devices and should not bias comparative analyses (Ranacher et al., 2016; Rychlicki et al., 2020). Field environments varied in topography, shade, vegetation, and resource distribution, each of which may influence movement independently of area. Weather conditions were mild and lacked extremes, limiting the detectability of strong temperature or precipitation effects. Social group size and composition differed across fields, meaning social dynamics may have interacted with field size to influence locomotion (Torres Borda et al., 2023; Brubaker et al., 2021). Despite these constraints, the dataset offers promising avenues for future research. GPS data span all of 2024, enabling analyses of circannual rhythms and seasonal environmental influences (Murphy, 2019).

Concurrent GPS sampling across individuals provides unique opportunities for studying equine social relationships. Proximity-based analyses could quantify preferred affiliations, avoidance patterns, or stable subgroup structures within herds. Prior work demonstrates that domestic horses form lasting social bonds, show partner preferences, and maintain affiliative networks even in managed environments (Waring, 2003; McDonnell, 2003; Torres Borda et al., 2023). By generating pairwise distance matrices and social network models, future analyses could identify compatible partnerships, detect early signs of social stress, and inform evidence-based group composition strategies, as social relationships and affiliative bonds play a central role in equine welfare and group stability (Torres Borda et al., 2023).

Spatially explicit analyses, such as co-occurrence around hay feeders, water sources, or shelter, could further reveal how environmental features shape social spacing. Resource-based movement patterns, such as travel between hay, water, shade, and terrain features, could clarify how horses navigate turnout environments. Integrating GPS with accelerometer-based behavioral monitoring would allow locomotion to be linked to broader time budgets involving grazing, resting, and social interaction (Maisonpierre et al., 2019; Matsubara et al., 2024).

## Conclusion

This study demonstrates that domestic horses' daily movement is shaped by a combination of spatial, environmental, and management factors. Field size produced the strongest effects, with moderately sized pastures supporting substantially greater and more naturalistic locomotion than very small enclosures. Horses also exhibited circadian patterns influenced by both inherent biological rhythms and predictable human routines. Weather, and specifically temperature, played only a modest role under the mild conditions studied.

Understanding how horses use space within managed environments supports welfare-oriented turnout practices, informs sustainable land stewardship, and builds a foundation for future analyses of resource use and social dynamics. As biologging tools become more accessible in equine management, integrating GPS and accelerometry will deepen our understanding of how domestic horses interact with and adapt to their environments, supporting science-based improvements in welfare and husbandry. Such applications of biologging data align with emerging approaches in applied welfare science, emphasizing the importance of both minimizing negative states and enabling positive social experiences (Mellor, 2017; McGreevy et al., 2018).

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