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An enclosure quality ranking framework for terrestrial animals in captivity

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ABSTRACT

There is a burgeoning interest in measuring and improving animal welfare in captive settings. Recent work has emphasized how enclosure design elements directly impact animal welfare (e.g., from health, behavioral, and reproductive standpoints). Yet, there is no published systematic way for practitioners to quantitatively rank enclosure quality. To address this critical need, we developed a flexible enclosure quality ranking framework for terrestrial animals in captivity. Our enclosure framework comprises 11 broadly applicable and measurable components of enclosure design that have relevance to animal welfare: Display, Size, Shelter, Materials, Environment, Climate, Viewshed, Social, People, Other, and Complexity. Each of these components relates to one or more of the "Five Freedoms" and "Opportunities to Thrive". In addition to developing the enclosure quality ranking framework, we provide an example of how to apply the framework, and offer suggestions on how to conduct empirical analyses with the ranking data derived from our framework. Once applied, our framework can be used to generate measurable outcomes that practitioners can use to make informed decisions, leading to optimal animal welfare.

1. Introduction

Welfare is a core and essential component of caring for terrestrial wildlife in zoos and similar wildlife care facilities. The definition of animal welfare has evolved over time as practitioners have developed a better understanding of how to provide for good welfare, but there is growing consensus that welfare centers on how an animal copes with the conditions in which it lives (Mellor et al., 2015). The "Five Freedoms" are often used to evaluate the welfare of an animal, and consist of the freedom from (1) hunger and thirst, (2) discomfort, (3) pain, injury, or disease, (4) freedom to express normal behavior, and (5) freedom from fear and distress (FAWC, 1979. The "Opportunities to Thrive" expands on the "Five Freedoms" by focusing on positive indicators of welfare, rather than the absence of negative ones, and are (1) strategically presented, well-balanced diet, (2) self-maintain, (3) optimal health, (4) expression of species-typical behavior, and (5) choice and control (Greggor et al., 2018).

Enclosure design has long been recognized as a major factor influencing welfare. Beginning around the 1960s and 70s, practitioners described how poor enclosure design leads to abnormal behaviors (Boorer, 2002; Meyer-Holzapfel, 1968; Morris, 1964). Meta-analyses of enrichment indicate that optimizing enclosure design is a leading strategy used to address welfare (Swaisgood and Shepherdson, 2005) and that enclosure characteristics can be effective at reducing the incidence of stereotypy performance (Swaisgood and Shepherdson, 2006). Other case studies have described enclosure effects on additional components of welfare in many taxa including amphibians (e.g., Holmes et al., 2016), ungulates (e.g., Wall and Hartley, 2017), mammals (e.g., Mason et al., 2001; Ross, 2006), and birds (e.g., Greggor et al., 2018; Woods et al., 2022). For example, frogs (*Xenopus laevis*) performed stress-indicating behaviors more frequently in tanks with white (vs. more naturalistic, black) backgrounds (Holmes et al., 2016). Enclosure size was positively linked to life expectancy in Burmese brow antlered deer (*Rucervus eldii thamin*) (Wall and Hartley, 2017). In farmed mink, the provision of water for swimming decreased cortisol levels (caged mink without the ability to swim had higher cortisol levels) (Mason et al., 2001). Additionally, passerine birds performed more stereotypical behaviors, and had higher corticosterone levels, under low-(compared to high-) frequency fluorescent lighting (Woods et al., 2022). Moreover, the vulnerability of species to reduced welfare in human care varies with taxonomic group and life-history strategy (Mason, 2010). For example, gentle and black lemurs (*Hapalemur* spp. and *Eulemur macaco*) in human

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Box 1
Glossary for the enclosure quality ranking framework's 11 Broad Components with example measurables for each BC. Relative strength of evidence is based on the publications identified during our non-comprehensive literature survey that were relevant to each BC within the enclosure quality ranking framework (See Table S1). While largely subjective, the relative strength of evidence is indicated here as an example and consideration to help practitioners decide whether to include and weight each BC as they quantify enclosure quality for their particular species and situation.

Broad component	Definition	Measurables	Relative strength of evidence
Display	Whether exhibit animals have off-display areas in their enclosure that can be accessed without caretaker assistance.	Binary (yes or no) to indicate whether an animal has access to off-display areas. Could also be measured on a continuous scale, as the proportion of on-display vs. off-display areas, the size of off-display areas, or count of off-display areas.	Relatively unstudied
Size	The dimensions of an enclosure such as its length, width, & height, total area, or volume of usable space for the animal.	Continuous (e.g., the total area, volume, or length/width/height as separate measurables to test if height is more important than length or area, for instance). Ordinal categories (small, medium, large) could also work as measurables here. Enclosure size could also be relative to an animal's body length, to make it more organism-centric.	Extensively studied
Shelter	Refuge provided by overhead cover, burrows, cavities, or other area providing thermoregulatory opportunities or used to hide from humans, potential predators, conspecifics, etc. Shelter includes the amount & type of cover (e.g., man-made, natural vegetation). Overhead cover can be used to evaluate access to sunny or shady areas in outdoor enclosures.	Continuous (e.g., the percentage of an enclosure with overhead cover) or numeric, such as the total number of shaded areas/burrows within an enclosure. Categorical data could be used to assess whether certain overhead cover materials affect welfare (e.g., artificial structures vs. naturalistic cover from trees), or burrow/cavity materials or dimensions influence welfare.	Moderately studied
Materials	The type of structural materials used to build an enclosure, including wall and ceiling materials as well as flooring or substrate type.	Categorical data for structural material types (e.g., wood, concrete, metal). Measurables relevant to wall materials may also include paint color, sound-dampening ability, and reflectivity (e.g., high/low reflectivity or quantified reflectivity using a spectrophotometer). Continuous measurables (e.g., the proportion of an enclosure with a certain substrate type or diversity indices for substrate types such as the Shannon-Weiner diversity index.	Extensively studied
Environment	The environmental characteristics of an enclosure, including, but not necessarily limited to, the type, amount, density, or diversity of vegetation in an enclosure and the types of water sources offered (e.g., pools, tubs of water, flowing water, and/or dynamic water sources). This component can also be used to capture the overall "artificialness vs. naturalness" of an enclosure.	Numeric (e.g., count data for the number of plants or water sources). Continuous (e.g., vegetation diversity or the total water volume). Categorical (e.g., dynamic vs. stagnant water sources or the overall naturalness vs. artificialness of an enclosure based on caretaker ratings).	Moderately studied
Climate	Humidity, temperature, precipitation, and photoperiod, particularly in indoor enclosures with simulated artificial conditions.	Mean, min, max, and s.d., in humidity, temperature, precipitation and photoperiod. Also may consider the composition of light (UV, red light, blue light, etc.). May consider seasonality.	Moderately studied
Viewshed	What an animal can presumably see outside of its enclosure within a reasonable area (e.g., within 10–20 m of an enclosure's perimeter).	Categorical (e.g., man-made structures, such as neighboring buildings, other enclosures, or natural (forests, fields, etc.) or continuous (e.g., the proportion of solid walls along an enclosure's perimeter, restricting an animal's viewshed).	Relatively unstudied
Social	The minimum distance between or among enclosures containing conspecifics or heterospecifics, which can be used to estimate social density as well as visual, auditory, or olfactory access to other animals in human care at the same zoo or facility. This BC excludes the social environment inside the enclosure because it is not a feature of the enclosure, but treat the exterior presence of conspecifics as a feature influencing enclosure inhabitants.	Continuous (e.g., distance measured with scale-appropriate units). Categorical (e.g., ordinal categories describing how near or far an enclosure is to other enclosures containing conspecifics or heterospecifics).	Extensively studied
People	Any human-related factor that could positively or negatively influence an animal while in its	Categorical (e.g., wood, concrete, dirt, or gravel caretaker pathways; easy vs. more difficult to	Extensively studied

Broad component	Definition	Measurables	Relative strength of evidence
	enclosure, such as noise from caretakers walking on enclosure floors, visual access to human pathways near the enclosure, proximity of the enclosure to service roads and guest pathways, ease of caretaker serviceability, and visual/auditory access or distance to zoo guests.	service, etc.) or continuous data (e.g., sound levels in decibels); could also include an estimate of the number of zoo guests passing an exhibit per unit time (e.g., daily, seasonally, annually).	
Other	Other enclosure characteristics that practitioners should rank but are not included elsewhere in the enclosure ranking framework.	Practitioner-determined. For example, feeding time, live animal handling practices, or addition or omission of chlorine in pool.	Relatively unstudied
Complexity	Structural complexity is not well-defined in the literature, but generally refers to the physical, structural, or temporal variation in an enclosure (may include plant diversity, topographic variability, shape differences, etc.). Complexity can also be used to capture visual differences among enclosures (e.g., a barren enclosure vs. one with many features such as plants, water sources, number of full or partial walls, etc.). With such broad applicability, complexity may serve as a type of composite ranking tool, since it inherently encompasses many enclosure characteristics, including those that are represented elsewhere in the enclosure quality ranking framework.	Continuous data such as the density and diversity of vegetation, topographic variation or digitally-measured complexity (e.g., based on JPEG file size, image file size ratios, etc.) Categorical (e.g., caretaker-rated structural complexity).	Moderately studied

care performed many abnormal or stereotypic behaviors, with poor reproduction (Petter, 1975). Conversely, ring-tailed lemurs (*Lemur catta*) had few behavioral and veterinary issues and high breeding success (Petter, 1975).

Despite the role of enclosure design on welfare, the mechanisms underpinning how specific enclosure characteristics influence welfare states within and among species are not well understood. Previous studies have largely consisted of case studies focused on one species or taxon (e.g., birds, "The Aviary Database Project," Bračko and King, 2014), but phylogenetic comparative analysis may be used to understand the biological mechanisms driving species-specific variation in their ability to cope with life in human care, providing information that can be used to optimize enclosure design (Mason, 2010; Mellor and Mason, 2023). However, case studies lack general principles and an applied framework which is important for practitioners to easily apply animal welfare science to species in their care. Current frameworks for evaluating enclosure quality center on quantifying how animals interact with their enclosures and the elements they contain (Decker et al., 2023). However, less emphasis has been given towards developing frameworks to systematically evaluate and rank enclosure characteristics based on *a priori* knowledge of an animal's life history to provide explanatory or predictive data for evaluating variation in behavioral indices of welfare.

We created an enclosure quality ranking framework for practitioners to better understand what makes an optimal enclosure for terrestrial species cared for in zoos and wildlife care facilities. We focus on relatively permanent design features and substrate choice in enclosures, not traditional enrichment such as novel objects and foraging enrichment. Our enclosure quality ranking framework will serve as a useful tool for improving welfare in a measurable way by helping practitioners to make informed decisions when improving enclosures, such as adding or modifying husbandry inputs, renovating existing enclosures, and constructing new enclosures. By developing and implementing a predictive approach that can be applied to all types of terrestrial enclosures, practitioners can systematically improve enclosures and the welfare of wildlife based on their specific needs.

2. Materials and methods

We developed our enclosure quality ranking framework by: (1) consulting published literature on enclosure characteristics that influence animals in captivity (from a health, behavior, reproductive, or other welfare-related standpoint), (2) developing a comprehensive list of biologically or ecologically meaningful enclosure characteristics for inclusion in the ranking framework (informed by our assessment of the literature), and (3) simplifying the comprehensive list of characteristics by combining them into a smaller set of broad, enclosure quality ranking components. Our literature survey, while not comprehensive, collated information to guide the development of an enclosure quality ranking framework comprehensive enough to rank all potential enclosure characteristics, flexible enough to be relevant to any enclosure housing terrestrial animals, and simple (intuitive) enough to be adopted by practitioners.

We conducted our literature search in Google Scholar using keywords such as: enclosure, habitat, zoo, captive propagation, animal care, captivity, welfare, and conservation breeding. At a minimum, we reviewed the Abstract of relevant peer-reviewed papers and published book chapters, and omitted papers without relevance to enclosure-related effects on terrestrial animals in human care (e.g., we omitted studies on fish). We also disregarded studies on farm animals and publications relevant to other user groups, such as zoo guests. We noted the species examined in each study and the enclosure characteristics evaluated. Additionally, we documented any suggested future research topics to provide insight into other enclosure characteristics that would be important to incorporate into our ranking framework.

Equipped with knowledge gained from the literature, we created an initial, comprehensive list of biologically or ecologically meaningful enclosure characteristics, along with specific examples of how each of the characteristics can be measured, which is an essential prerequisite to ranking enclosure quality. We used our initial list of enclosure characteristics to formulate our final enclosure quality ranking framework and provide a worked example to demonstrate how to implement the framework, along with specific suggestions on how practitioners can approach enclosure–welfare analyses under real-world scenarios (i.e., most likely involving diverse animal care settings, convoluted data structures, and small sample sizes).

3. Results and discussion

3.1. The enclosure quality ranking framework

Because many of the enclosure characteristics in our initial comprehensive list were closely related proxies or covariates for one another, we lumped the list of enclosure quality characteristics into 11 Broad Components (BCs), comprising our final enclosure quality ranking framework: Display, Size, Shelter, Materials, Environment, Climate, Viewshed, Social, People, Other, and Complexity. A list of the enclosure characteristics used to create the framework (and associated publications) is provided in the Supplementary Material (Table S1). The definitions of the BCs and examples of how practitioners could measure each BC are provided in Box 1. Illustrations with examples of each BC are in Fig. 1. Regarding the measurables, a relatively simple example is the size of an enclosure (see the Size BC in Box 1), which could be quantitatively measured or grouped into ordinal categories (e.g., large, medium, or small) (Box 1). The relevant size measure depends on the species' habitat use patterns and mode of transportation; for example, a vertical dimension would be important for birds and primates but less so for a ground-living armadillo. It is important to note that the BCs are inherently not (entirely) mutually exclusive, so some enclosure characteristics could be evaluated with more than one BC (e.g., the quality of water sources and vegetation could be ranked by the Environment BC or the Complexity BC). However, each of the BCs can be used to rank different aspects of an enclosure despite their inherent interconnectedness. The decision of whether to rank an enclosure characteristic with more than one BC would likely depend on the goal of the enclosure quality assessment and expected interpretability of the results. Practitioners who choose to rank one enclosure characteristic or input with more than one BC should be cautious that doing so will not unduly inflate the enclosure quality ranking, for example, by giving credit to a characteristic, such as the presence of trees, twice in the framework (say, once in the Environment BC and again in the Shelter BC). However, a slight reframing of how a characteristic is evaluated across more than one BC can circumvent redundancy and inflated enclosure quality scores (e.g., using the diversity of tree species as the characteristic under the Environment BC and the presence of shelter provided by trees vs. other structures under the Shelter BC). In situations where it is unclear whether and how to evaluate an enclosure characteristic across more than one BC, we recommend that practitioners restrict evaluating that characteristic to within one BC that is the most appropriate for their purposes.

3.2. Implementation

The precise steps needed to implement our enclosure quality ranking framework will ultimately be best determined by practitioners on a case-by-case basis. Here, we offer a general process and guidelines for using the ranking framework as an enclosure quality assessment tool (see also worked example in Box 2):

1) Identify characteristics within each BC that are relevant to an enclosure and, ideally, are biologically or ecologically meaningful to the species based on previous studies or *a priori* hypotheses. It is important to keep in mind that not all of the 11 BCs will be relevant to every enclosure; those without relevance should be omitted from the ranking process at the discretion of the practitioner(s).
2) Decide how to measure the characteristics within each of the BCs (i.e., using measurement tools or practitioner-defined categories).
3) Measure the characteristics within each BC identified in the previous step.
4) After all measurements (data) have been recorded, calculate a cumulative enclosure quality score, if desired. This will require categorizing all measurables (including those measured on a discrete, numeric, or continuous scale) and subsequently assigning numeric ranks to each category, which can then be summed (and weighted, as appropriate) to create a cumulative enclosure quality score.

3.3. Evaluation

There may be cases when practitioners use our enclosure quality ranking framework as a tool to inform welfare decisions that do not require a formal analysis. For example, our framework could be applied to a single enclosure housing one animal that frequently paces (a known stress/stereotypical behavior) to identify the enclosure characteristic linked to the pacing behavior. From there, remedial actions could be taken to improve the enclosure and reduce or, ideally, eliminate pacing such as providing new sheltered areas or altering the enclosure's overall complexity. Further, collection of these data using a standardized framework will greatly expand the potential for cross-study meta-analyses that will be essential to building an understanding of the relationship between enclosure characteristics and welfare and reproductive consequences (Mason, 2010; Swaisgood and Shepherdson, 2006).

When our enclosure quality ranking framework is used with the intention of performing a formal analysis, the ranking data created with our framework (i.e., independent variables/predictors or potential fixed effects) should ideally explain variation in the response variable of interest, e.g., performance of stereotypies, variation in space use, reproductive outcomes, etc. Resulting analyses may use the ranking data or, alternatively, the raw enclosure data, thus it is important that both be reported in publications for facilitate future meta-analyses. Practitioners must first determine the type of variable structure that lends itself to the most meaningful analysis (e.g., categorical small, medium, large variables for enclosure size vs. continuous data, or the rankings developed with the enclosure quality ranking framework, at the BC level, or the overall cumulative enclosure quality scores; see Box 2). When categories are used, practitioners should select categorical boundaries based on the data, and if deemed necessary, use analytical approaches to boundary detection (e.g., breakpoint analysis, regression tree analysis, or k-means cluster analysis). The decision on variable structure could be based on the expected predictive or explanatory value of the variable in question or how variable structure might influence the interpretation of the results needed to guide management decisions. If the choice of variable structure is unclear, it is possible to employ an analytical approach to determine if a certain variable structure is superior to others, for example, using forward or backward selection to choose one variable structure or the other (e.g., Flanagan et al., 2019).

Some scenarios will benefit from variable weighting when there is *a priori* knowledge that certain enclosure characteristics likely have a greater impact on animal welfare relative to other enclosure characteristics. Deciding which variables to weight and to what extent must ultimately be practitioner-determined and ideally informed by previous research (see Box 1 for recommendations). As with any analysis, it will also be critical to test for multicollinearity if the analysis includes several possible predictors. This can be achieved using Pearson correlation tests, assessment of variance inflation factors (e.g., Zuur et al., 2009), or combining covarying predictors (e.g., ratings from inherently interconnected BCs) with Principal Components Analysis, for example. Another important consideration for practitioners when utilizing many predictors in a single analysis, is model overfitting, which often leads to the dreaded convergence error in so many R packages (e.g., Barton, 2018; Bates et al., 2015; Christensen, 2018). There are numerous ways to develop or identify the most parsimonious model, for example, using penalized regression (among other approaches involving cross-validation) or an information theoretic approach with model comparison criteria such as the Akaike Information Criterion (AIC) (e.g., Burnham and Anderson, 2002).

Identifying biologically meaningful results could be based on statistical significance in some cases or each variable's relative importance score if an information theoretic framework (e.g., involving model averaging) is utilized. When statistical relationships are identified, we recommend "embracing uncertainty" around parameter estimates, by reporting standard errors and confidence limits (e.g., confidence intervals that overlap 0 suggest a "significant" explanatory variable or fixed effect is an unreliable predictor of the response variable used in an analysis). Of course, all of the aforementioned approaches require sufficient sample sizes (e.g., a mixed-effects model should have a minimum of 10 observations per fixed effect) (Grueber et al., 2011). Studies with sample size limitations are obviously common for animals kept in human care (Swaisgood and Shepherdson, 2005), so practitioners working with very small sample sizes may be limited to evaluating enclosure effects with simple summary statistics, frequentist statistics, or more sophisticated approaches involving Bayesian analyses (McNeish, 2016). Alternatively, practitioners could increase sample sizes by designing collaborative studies that involve the same species of animal at multiple zoos. Animals are also rarely randomly assigned to enclosures, another statistical caveat, and we recommend that practitioners responsible for the dissemination of results be transparent about this analysis limitation.

3.4. General discussion

Enclosure design characteristics are universally acknowledged as major drivers of animal welfare, with strong links to the Five Freedoms and Opportunities to Thrive (FAW, 1979; Greggor et al., 2018). Yet, we are unaware of any meta-analyses or systematic reviews targeting the role of enclosure characteristics as determinants of welfare (but see recent comprehensive review on the potential importance of enclosure complexity by de Azevedo et al., 2023), and instead have only informative quantitative anecdotes. We hope our framework will facilitate the collection of new data on enclosure impacts, allowing future cross-study insights to be more readily drawn, with broad and important (taxonomically relevant) revelations for how we design and furnish enclosures. By lumping numerous, diverse enclosure characteristics into 11 BCs: Display, Size, Shelter, Materials, Environment, Climate, Viewshed, Social, People, Other, and Complexity, our framework comprehensively captures enclosure quality criteria in a relatively simplified way, increasing the likelihood that practitioners will apply our framework. Importantly, our choice of BCs was based on documented enclosure impacts on animal welfare (Table S1). To ensure that the enclosure rankings derived from our framework are meaningful, we suggest practitioners only apply a BC when a useful management implication can be identified, and, ideally, one that can be empirically evaluated through hypothesis testing. Below we offer key messages for each BC, highlighting recommendations for how results may be applied.

Previous studies incorporating elements of our Display BC have demonstrated that this can be an influential variable. When given access to off-exhibit indoor dens, giant pandas (*Ailuropoda melanoleuca)* displayed fewer signs of behavioral agitation and lower cortisol levels associated with stress (Owen et al., 2005) compared to when confined on exhibit. Additionally, cranes (*Grus canadensis*, *Grus americana,* and others) held on-display produced significantly fewer eggs than off-display birds (Mirande et al., 1996). More work is needed to understand the role of providing enclosures with off-display options, but we recommend that practitioners endeavor to provide off-display areas either as an untested best practice, or as an opportunity further evaluate the importance of this BC.

We anticipate inter-species (and perhaps inter-individual) variation with our Size BC. Wide-ranging ground-living species in nature will likely be influenced by enclosure area (e.g., Clubb and Mason, 2003). When polar bears (*Ursus maritimus*) were provided sufficient space to maintain interindividual distances, they displayed less aggression (Renner and Kelly, 2006). Conversely, larger enclosures have been linked to stress in prey animals, such as small rodents (Morgan and Tromborg, 2007). We recommend practitioners consider the primary mode of locomotion, home range size, and habitat use of the species when evaluating the relative contributions of different aspects of enclosure size to welfare, with the ultimate goal of determining taxa-specific optimal enclosure dimensions.

A common belief in zoo welfare is that it is not the size that counts, but rather the quality of the environment in the enclosure. Our BCs target elements related to quality, including the Shelter and Materials BCs. Shelter can take different forms—such as overhead canopy, or shrubs, burrow, or tree cavity to hide behind or within. Shelter may also be particularly important for animals that exhibit behavioral thermoregulation. Burrows (Shelter BC) and bedding used to construct burrows (Materials BC) influence welfare in rodent species (reviewed in Morgan and Tromborg, 2007), and similarly leaf litter might serve a parallel role in amphibians (Michaels et al., 2014). Substrate types in enclosures (Materials BC) also affect the behavior and health of animals. For example, floor type had notable foot health consequences in some elephant species (e.g., *Loxodonta africana* and *Elephas maximus*) (Boyle et al., 2015; Haspeslagh et al., 2013). Moreover, certain substrate types encourage behaviors indicative of positive welfare such as foraging (e.g., biofloors for great apes, many species; see Leinwand et al., 2021). These studies highlight the value of ensuring animals have access to shelter and appropriate substrate materials, which can be added retroactively (Wark et al., 2020).

Vegetation and water sources take center stage in the literature addressing the Environment BC. Plants can serve as effective visual barriers (see also BC Shelter above) for chimpanzees (*Pan troglodytes*) from conspecifics and zoo visitors, and offer safe zones for subordinate male chimpanzees to mate out-of-sight of alpha-males (Wehnelt et al., 2006), potentially increasing the genetic health of the troop. In another study, female hippos (*Hippopotamus amphibius*) preferred areas with water ~ 0.6–1 m deep (Blowers et al., 2010). Thus, access to water and plants, ranked with the Environment BC, can enable practitioners to obtain desired welfare outcomes.

The Climate BC applies to indoor, climate-controlled enclosures to assess climatic effects (e.g., temperature) and correlates (e.g., light) on welfare. Artificial heat effectively maintains winter-time body temperatures in tortoises (*Aldabrachelys gigantea*) at levels similar to those of wild counterparts (Falcón et al., 2018). Ultraviolet light is critical for the health of some animals. Reptiles and amphibians require ultraviolet radiation to facilitate calcium absorption from their food and make vitamin D3 (reviewed in Baines et al., 2016). Thus, enclosures with low ranks in the Climate BC could be improved by modifying the types of heat and light sources available, keeping in mind potential adverse effects of providing blue light to nocturnal animals (Fuller et al., 2016). Alternatively, animals could be strategically moved to enclosures, wherever possible, with conditions ranking higher in the Climate BC for the species than other available enclosures.

Our Viewshed BC captures the degree of natural vs. human-built materials an animal is able to see outside of its enclosure. In humans, a view of nature outside a window has important physical and mental health consequences (Soderlund and Newman, 2015). It seems plausible that the same may apply for many animal species, although this area of research and application in animals has been understudied. Elevating enclosure spaces relative to human walkways and viewing areas is an example of an intentional viewshed modification motivated by assumptions about animal perceptions (Grazian, 2012). Without substantial empirical backing to support a role for viewshed in welfare outcomes, our primary recommendation for this BC is the development of research programs and management interventions to determine its importance. When feasible, practitioners should endeavor to improve the animal's viewshed, such as by planting trees, installing visual barriers, or making other enhancements to the viewshed guided by knowledge of the species' natural behavior, wild habitat, and perceptual world.

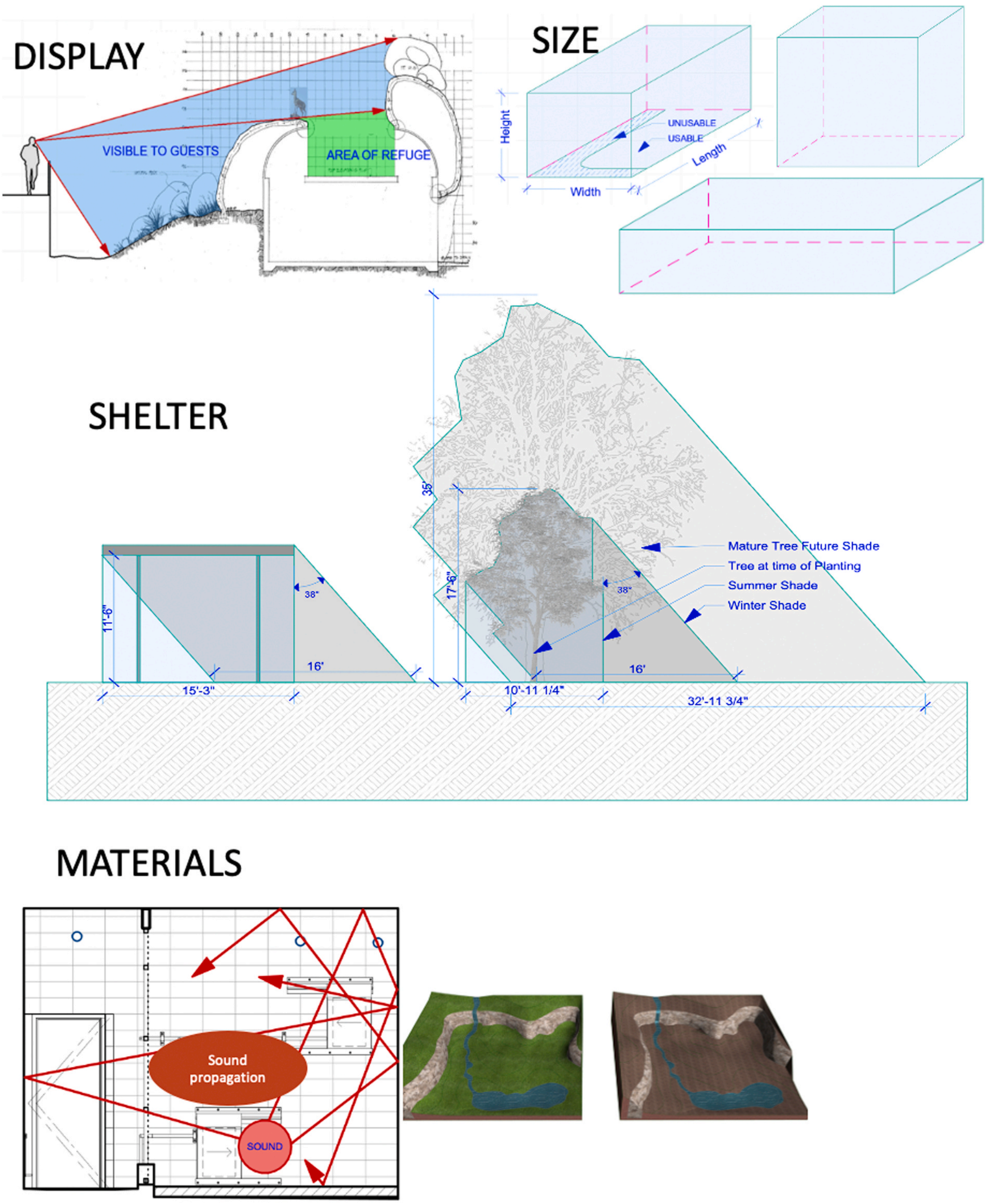

Fig. 1. Illustrations showing example(s) of each Broad Component used for evaluation enclosure quality. Display: An exhibit with access to an off-display area of refuge. Size: Simple rectangular enclosures with varying dimensions of length, width, and height. Shelter: Shade sail and a tree, with shadow projections based on tree growth estimates. Materials: Sound propagation map illustrating the projected acoustic characteristics of an indoor enclosure, as well as two identical enclosures with different substrate types. Environment: Enclosure with a variety of vegetation. Climate: Enclosure with projected UV light paths. Viewshed: The projected sightlines of animals. Social: Enclosures spaced uniformly at variable geographic distances (further apart, left or in very close proximity, right). People: The proximity of guests to a glass enclosed polar bear exhibit. Complexity: Aerial views of enclosures with varying complexity levels based on shape and water source types alone. Image credits: Christopher Zolezzi and the San Diego Zoo Wildlife Alliance.

Two additional BCs also exterior to the enclosure (the Social and People BCs) account for the presence of neighboring animals or people. The social environment, while not a characteristic of an enclosure itself, is well-known for its influence on welfare and reproduction (Carlstead and Shepherdson, 1994). Yet, social influences driven by the arrangement of enclosures containing conspecifics, have received little

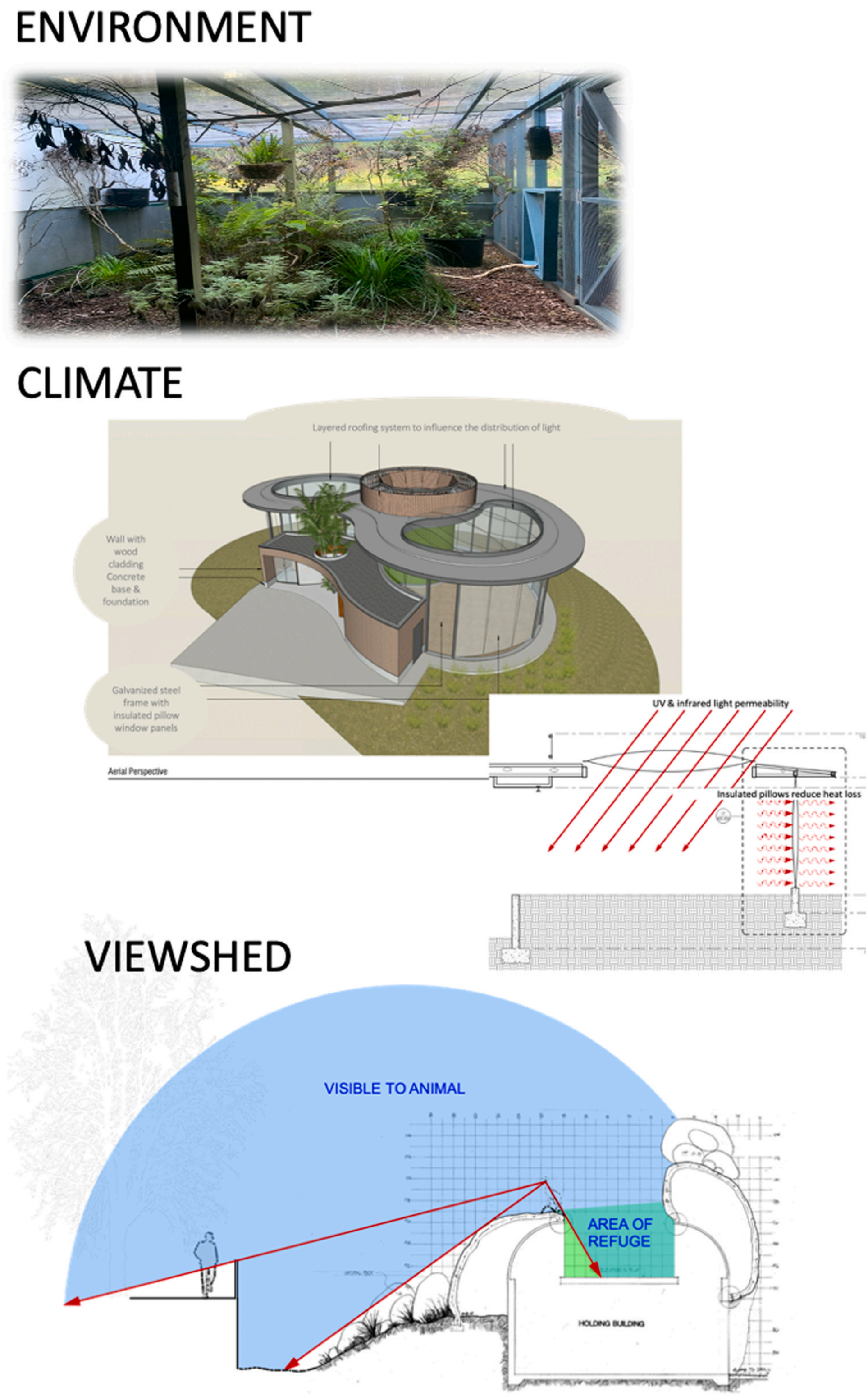

Fig. 1. (*continued*).

empirical attention. In the Hawaiian Crow ('Alalā, *Corvus hawaiiensis*) birds in aviaries that were farther apart from other aviaries containing conspecifics experienced better reproductive success than those living closer to neighboring aviaries (Flanagan et al., 2020). The People BC is best exemplified by the effects of zoo visitors (Chamove et al., 1988) and can be associated with distance from enclosure, human behavior, and noise levels. Human caretaker impacts on enclosure inhabitants must also be considered. For example, caretaker pathways made of loose materials, such as gravel or cinder, are noisier to walk on than solid floors (e.g., made of concrete), which could disturb animals and thus practitioners could replace noisy floor materials with quieter ones. The People BC could also capture enclosure characteristics that may

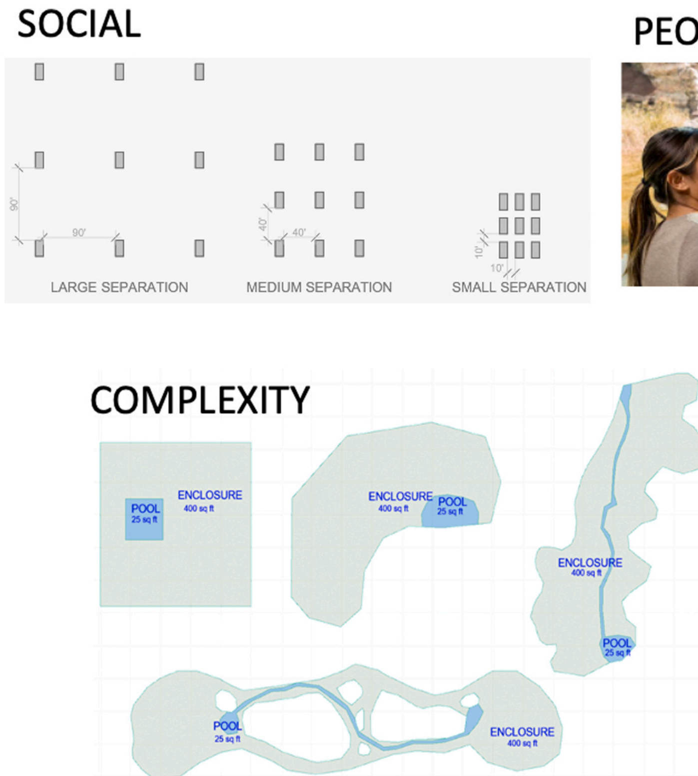

Fig. 1. (*continued*).

positively influence animal welfare, such as ease of husbandry and care, if it is linked to better animal care. We recommend more research is focused on these other potential influences arising from factors outside the enclosure.

Finally, the Complexity BC facilitates ranking multiple enclosure characteristics (including those that may be impractical to measure) in an integrated, holistic way. Complexity accounts for the number and diversity of features, such as the number of principal axes (Sambrook and Buchanan-Smith, 1997), comprising physical geometry and the inclusion of diverse biotic and abiotic components (de Azevedo et al., 2023). Scott and LaDue (2019) found that Asian elephant (*Elephas maximus*) activity levels (a positive welfare indicator), were higher in more complex enclosures with a variety of shade structures and diverse substrates (Scott and LaDue, 2019). Most effects of complexity are associated with positive outcomes (de Azevedo et al., 2023). Evaluating complexity may indeed take an "everything-but-the-kitchen-sink" approach (sensu Swaisgood and Shepherdson, 2005), making the disentanglement of variables important for welfare challenging. However, this approach will increase the likelihood of incorporating important variables for individual animals. Thus, we recommend effort to make the measurement of complexity feasible, such as the use photo file size, a proxy for the total amount of information contained (Ritzler, 2022), or caretaker subjective ratings.

4. Conclusions

Our enclosure quality ranking framework has several implications for on-the-ground application. Application of this framework will also make the evaluation of enclosures more transparent, allowing multiple stakeholders involved in enclosure creation to see the same set of variables and how they are evaluated, weighted and ranked. In this regard, the process mirrors that of a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis as it has been applied to assessing the relative merits of potential receiver sites (that have even more complex habitat variables than wildlife enclosures) for conservation translocations (Chock et al., 2022; White et al., 2015). In fact, our BCs could be incorporated into a SWOT framework in lieu of statistical evaluation, capturing the expert opinions of multiple stakeholders. The information generated from our framework can be used to guide decisions about where to house animals and improving existing enclosure conditions. Moreover, our framework offers a standardized approach for pinpointing the shortcomings of an enclosure and a means to "learn from the past", such as, designing new enclosures based on lessons learned from animals kept in enclosures determined to be suboptimal (Marshall et al., 2016). Recent calls for more dynamic, outcome-based husbandry (Vicino et al., 2022) necessitate the importance of understanding how enclosures characteristics affect welfare, ideally with quantitative methods such as the application of our framework. We hope that our framework will be used to generate measurable results that empower practitioners to make informed decisions, ultimately leading to optimal animal welfare.

While we do not provide new empirical results to apply to improve welfare, our intent is to help cultivate a standardized approach to address the relative dearth of information on the impacts of enclosure characteristics on animal welfare. Although our enclosure ranking system necessarily entails some subjectivity, we have tried to

Box 2
An example demonstrating the application of enclosure quality ranking framework to compare four hypothetical enclosures, each used to house a single pair of the same species. Not all of the BCs are relevant to the hypothetical enclosures presented in this worked example, and thus were not included.

Hypothetical enclosure descriptions

Enclosure 1: This outdoor enclosure is on-display but has off-display areas. It is a large enclosure with one area containing overhead cover & medium caretaker-rated visual complexity. It has > 50% natural substrate and > 75% visual access to nature, and is in close proximity to neighboring enclosures with conspecifics. It is also located near roads.

Enclosure 2: This outdoor enclosure is on-display but has off-display areas. It is a small enclosure with four areas containing overhead cover & low caretaker-rated visual complexity. It has < 50% natural substrate and > 75% visual access to nature, and is in close proximity to neighboring enclosures with conspecifics. It is also located far from roads.

Enclosure 3: This outdoor enclosure is on-display but has off-display areas. It is a large enclosure with five areas containing overhead cover & medium caretaker-rated visual complexity. It has > 50% natural substrate and > 75% visual access to nature, and is far away (distant) from neighboring enclosures with conspecifics. It is also located near roads.

Enclosure 4: This outdoor enclosure is on-display without access to off-display areas. It is a large enclosure with four areas containing overhead cover & high caretaker-rated visual complexity. It has > 50% natural substrate and < 50% visual access to nature, and is far away (distant) from neighboring enclosures with conspecifics. It is also located near roads.

Step 1) Identify BCs and underpinning relevant characteristics that have applicability to all enclosures. Step 2) Collect data (e.g., see "Measurements" column below). Step 3) Rank each component by assigning numeric scores to practitioner-defined categories (ideally derived from the data collected; see "Numeric scores" column below).

Broad components	Relevant characteristics	Measurements	Numeric scores (based on measurements)
Display ✓	Access to off-display areas	Categorical (Yes or No) indicating access to off-display areas	Yes = 1, No = 0
Size ✓	Overall dimensions	Volume (cubic meters)	Categorized & numerically coded as Small = 1, Medium = 2, or Large = 3
Shelter ✓	Thermal refuge (access to sunny & shady areas)	Count of areas with overhead cover separated by ≥ 1 meter	< 3 = 1 or ≥ 3 = 2
Materials ✓	Substrate type	Proportion of natural (as opposed to artificial) substrate	< 50% = 1 or ≥ 50% = 2
Complexity ✓	Visual complexity	Caretaker-ranked categories (Low, Medium, or High)	Low = 1, Medium = 2, or High = 3
Environment X	N/A	N/A	N/A
Climate X	N/A	N/A	N/A
Viewshed ✓	Visual access to nature	Categorical (Yes or No) indicating access to a minimum of > 50% natural viewshed	Yes = 1, No = 0
Social ✓	Proximity to conspecifics	Distance in meters to conspecifics	Categorized & numerically coded as Close = 1 or Distant = 2
People ✓	Proximity to anthropogenic noise	Distance to roads in meters	Categorized & numerically coded as Near = 1 or Far = 2
Other X	N/A	N/A	N/A

To facilitate interpretability of results, we recommend assigning higher numeric values to categories linked to *a priori* hypotheses with positive outcomes on the response variable of interest (e.g., reproduction, health, etc.).

The green checkmarks indicate relevant BCs to the hypothetical enclosures. The red Xs indicate irrelevant BCs in this worked example. The characteristics underpinning each BC are listed, as well as the example measurables and associated categories for ranking each BC with numeric scores.

Step 4) If desired, use the resulting enclosure quality ranking dataset to calculate a cumulative quality score for each enclosure (by summing across the numeric scores for each BC).

Hypothetical enclosure	Display	Size*	Shelter*	Materials*	Complexity	Environment	Climate	Viewshed	Social*	People*	Other	Cumulative enclosure quality score
Enclosure 1	1	3	1	2	2	N/A	N/A	1	1	1	N/A	12
Enclosure 2	1	1	2	1	1	N/A	N/A	1	1	2	N/A	10
Enclosure 3	1	3	2	2	2	N/A	N/A	1	2	1	N/A	14
Enclosure 4	0	3	2	2	3	N/A	N/A	0	2	1	N/A	13

* These numerically coded categories could also be evaluated using raw measured variables such as discrete count data or continues data such as percentages or proportions. The practioner-defined categories for each BC (used to rank each component) should be guided by data whenever possible. These concepts are described in more detail under the "Evaluation" section.

operationalize the process as much as possible. A standardized approach such as ours may serve as a catalyst for renewed interest in documenting the effects of enclosures on animal welfare and provide a more structured and consistent foundation to ensure that results can be compared, contrasted, and combined for new analysis, moving forward the science of animal welfare in a more robust manner. Like any applied science, animal welfare science should strive to determine what works and what doesn't. When this framework is applied, the animal welfare community should benefit from improved understanding of how these enclosure characteristics influence welfare and suggest testable management interventions where specific enclosure characteristics are experimentally manipulated to determine their efficacy at improving welfare. Ultimately, we envision enclosure design guidelines that are sensitive to taxonomic, life history, and individual variables that govern the relevance of specific enclosure characteristics for species and individuals.

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Declaration of Competing Interest

The authors declare no conflict of interests.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.applanim.2024.106378.

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