

The Welfare Footprint Framework: Quantifying Animal Experience to Guide Ethical and Policy Decisions

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Abstract

The assessment of animal welfare has long been challenged by the difficulty of quantifying subjective affective experiences in a standardized and comparable manner. Traditional models often rely on scoring systems or human valuations that lack a common, universally understood unit, hindering objective comparisons of welfare across conditions and species. The Welfare Footprint Framework (WFF) addresses this gap by providing a scientifically robust methodology for assessing and quantifying animal welfare. It offers a comparable and biologically meaningful measure that directly connects to animal experience: cumulative time spent in affective states of varying intensities, both negative ('Pain') and positive ('Pleasure'). This is achieved through a process that includes: (I) a detailed description of the living conditions and/or processes being evaluated; (II) an inventory of their biological consequences for the animals and resulting affective experiences; (III) the quantification of each affective experience in terms of intensity and duration using rigorous evidentiary standards; (IV) an epidemiological investigation of each experience in the target population; and (V) the standardization of estimates per animal, system, or unit of product. The WFF allows for comprehensive coverage of all domains of animal experience, and can be applied across entire production chains or other settings where animals are used, to any geographical level (farms, countries, globally), and to any sentient species. This transparent, evidence-based approach makes all assumptions explicit, highlights knowledge gaps, and allows for meaningful comparisons across species, systems, and interventions. Its practical utility has been demonstrated in diverse applications, from quantifying the welfare impact of transitioning to cage-free housing in egg-laying hens, to evaluating slower-growing broiler breeds, to assessing fish slaughter methods. In addition to its scientific value, the framework offers the public a means to clearly understand how sentient organisms experience different conditions using familiar and intuitive metrics, facilitating the ethical alignment of societal values with evidence about animals' experiential realities.

Introduction

As scientific and legal acknowledgment of animal sentience expands, society confronts the challenge of developing ethically robust policies and standards that meaningfully incorporate animal welfare (Richter et al., 2024; Rowan et al., 2021; Tuytens et al., 2025). This requires more than recognizing animals' capacity for sentience; it demands evidence-based methodologies that enable quantifying and comparing the extent to which their welfare experiences are affected by multiple and diverse conditions. Yet, unlike public health or environmental science, which rely on standardized metrics like Disability-Adjusted Life Years (DALYs) or environmental footprints to quantify human health and environmental impacts, animal welfare assessment has long lacked a common currency for measuring and comparing welfare impacts across practices, systems, products or policies. This gap hinders researchers, producers, advocates, policymakers and consumers from objectively evaluating trade-offs, prioritizing interventions that maximize welfare gains within resource constraints, and grounding decisions in a transparent understanding of animals' lived experiences.

A common currency for animal welfare requires a clear definition of what welfare entails (van der Staay et al., 2025). At its core, animal welfare is about the animals' lived experiences, namely the positive (pleasant) and negative (unpleasant) affective experiences animals endure over time, such as physical pain, fear, frustration and joy (Browning, 2020; Duncan, 1996; Duncan, 2006; Mason & Mendi, 1993; Mellor, 2017; Reimert et al., 2023; Rowan et al., 2021). Unlike economic outcomes, disease burden metrics or environmental impacts, these experiences are inherently subjective, requiring inference from indirect indicators of well-being (Broom, 1986; Browning, 2023; Dawkins, 2004; Duncan, 2006; Harnad, 2016a; Mason & Mendi, 1993), including behavior, physiology, neurology, and pharmacology, which are species-specific and often emerge from multifactorial causes. Such complexity has hindered the development of a welfare measure that could be universally applicable.

Given these challenges, many existing welfare assessment frameworks adopt pragmatic strategies, organizing assessments around discrete domains or criteria, including health, housing, nutrition, and behavior. Each criteria or domain is then evaluated based on selected indicators, which are often subjectively weighted and aggregated into composite scores. Among these models are the [Welfare Quality®](#) protocol (Blokhuys et al., 2010; Welfare Quality Consortium, 2009), the Five Domains model (Mellor, 2017; Mellor & Beausoleil, 2015), the Animal Needs Index (Bartussek, 1999, 2001), and various decision-support systems (Blokhuys et al., 2007; Bracke et al., 2001, 2002; Stien et al., 2013). Widely applied in research and farm auditing contexts, these models reflect broad scientific consensus on core criteria for welfare assessment, and are critical for identifying areas of concern and guiding improvements, helping track and ensure compliance with a set of welfare standards. However, scoring systems are limited in their ability to support broader comparisons of welfare; scores are abstract, context-dependent, and do not express welfare impacts in commensurate or familiar terms, limiting their use in policy, communication and decision-making settings in general. Additionally, the use of pre-established domains or criteria, where each contributes only with a bounded portion to the overall score, creates a ceiling effect: no matter how severe or prolonged a welfare issue

may be within a single domain, its impact is capped by design. Finally, the temporal dimension of welfare is often neglected. Although farm visits and audits require instantaneous assessments, every welfare experience happens over time. Yet aggregate scoring models typically treat them as static, without accounting for how long they last or how early in life they emerge.

The European Food Safety Authority (EFSA) has advanced a more granular, risk assessment-based approach, widely applied in the evaluation of farmed animal welfare (Bøtner et al., 2012). EFSA's method scores the intensity, duration, and likelihood of each welfare consequence identified as relevant, combining intensity and duration scores multiplicatively to derive an overall severity of each consequence. This structure makes the relative contribution of these welfare dimensions (time and intensity) explicit, while grounding assessment in comprehensive literature reviews and expert elicitation. Yet, scores are context-dependent and expressed in abstract form, whose meaning is not intuitively interpretable outside the assessment context. Furthermore, EFSA does not integrate the impact of multiple welfare challenges into an overall welfare impact metric. As a result, while EFSA's framework excels as a structured hazard characterization, its outputs are not directly commensurate across production conditions or species, and are less suited for direct communication in familiar terms.

The Welfare Footprint Framework (WFF) was developed to address this critical need by providing a structured, evidentiary pathway from observable welfare indicators to quantitative claims about affective experience. Just as DALYs and Quality-Adjusted Life Years (QALYs) transformed public health by creating a common currency to compare diverse health and life conditions, the WFF introduces a common currency for animal welfare: cumulative time spent in affective states, both negative and positive, of varying intensities. But unlike DALYs and QALYs, which are grounded in functional domains of life such as health status and the ability to perform daily activities, the WFF is based on the measurement of affective experiences, capturing the fundamental dimension of welfare that functional metrics leave unmeasured. Importantly, by expressing welfare in units of time, which is a universal, additive, meaningful and intuitive metric, the framework allows multiple affective experiences to be compared and combined into a cumulative quantitative measure—a natural aggregation of welfare impacts over any timeframe of interest.

One natural application of the WFF is the quantification of the animal welfare cost embedded in animal-sourced products. By calculating cumulative affective burdens endured by all animals used in the production cycle, the framework yields a product's Welfare Footprint, enabling comparisons of welfare impacts in units like kilograms or liters. WFF metrics are also applicable beyond agriculture to any contexts where sentient experiences matter, including wild, companion, research, or work animals, and even human populations. Its modular design adapts to diverse assessment scopes, from the welfare impact of single conditions at the individual level to the net welfare effects of policies and standards for different animal populations. By grounding assessment in the core dimensions of affective experience (valence, intensity, and duration) the framework also provides a transparent methodological contribution to the empirical study of sentience. It does so by requiring that inferences about what animals feel be made explicit, based on evidence, and expressed in terms that are biologically meaningful and relatable. Its evidentiary rigor also makes it valuable in settings that demand documentation of

prolonged or severe pain and distress (e.g., to establish criminal liability).

This paper formally introduces the methodological structure and intended applications of the Welfare Footprint Framework. While the initial versions of the framework (Alonso & Schuck-Paim, 2021a, 2021b) have already been applied in the assessment of the welfare impact of key reforms in poultry (Schuck-Paim & Alonso, 2021; Khire & Ryba, 2025; Schuck-Paim, et al., 2025a; Schuck-Paim & Alonso, 2022) and fish welfare (Schuck-Paim, et al., 2025b), this is the first complete description of its core analytical modules, strengths, and limitations. We begin by outlining how the WFF organizes existing knowledge of animal production, to then translate evidence from animal welfare science and other disciplines into time-based metrics of affective experience. We then illustrate how it provides a common currency for welfare that allows for integration into economic, environmental and policy analysis, making the evidentiary basis for claims about affective experience in sentient organisms explicit, structured, and open to scrutiny, an approach grounded in epistemic humility about current knowledge while adaptable to future evidence. This work is presented as a foundational methodology, intended to be challenged and refined to advance the scientific study of animal sentience.

Analytical Architecture of the Welfare Footprint Framework

To be scientifically robust and useful for decision-making, any footprint metric, whether for water, pollution or welfare, must be grounded in a structured and replicable accounting methodology (Čuček et al., 2012; Global Footprint Network, 2009; Manfredi et al., 2015). Such a framework must be comprehensive enough to capture all significant impacts within a system while remaining flexible enough to be applied across diverse contexts.

The WFF provides this structure through seven interconnected analytical modules (Figure 1), which guide the analysis through a logical sequence: beginning with a detailed description of the animal's environment and living conditions (I. Zootechnical Description), followed by the identification of their Biological Consequences (II. Veterinary Inventory). Each of the resulting affective experiences, both negative and positive, is then identified and quantified in terms of its estimated intensity and duration (III. Affective Quantification). Next, the population-level burden of each affective experience is estimated by weighting it by its prevalence within the population, geography and timeframe of choice (IV. Epidemiological Review). The cumulative burden from all positive and negative experiences can then be combined, and standardized by productivity metrics to produce a Welfare Footprint per unit of product (V. Econometric Calculation). A notation module ensures that all results are expressed transparently, with full documentation of analytical boundaries and assumptions for use by consumers, certification bodies, advocates, industry, and regulators (VI. Welfare Footprint Expression and Notation). A final, optional module (Ψ. Interspecific Scaling) addresses the challenge of interspecific comparisons, providing a transparent and flexible mechanism to account for potential differences in affective capacity and time perception across species.

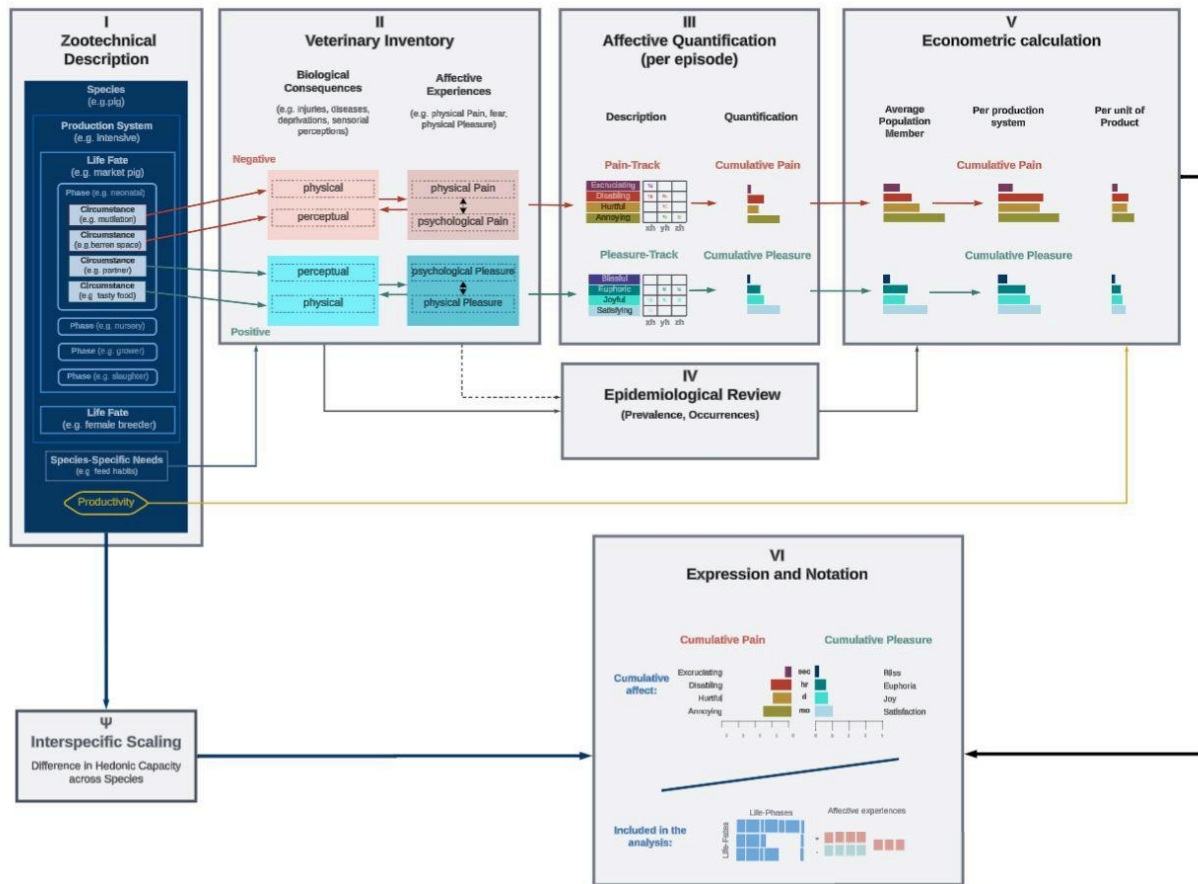


Figure 1. Analytical Flowchart of the Welfare Footprint Framework. This diagram outlines the step-by-step process of calculating a Welfare Footprint, from describing living conditions to quantifying welfare per unit of animal product. See text for details.

The following sections detail each module. Key terms are capitalized to distinguish their technical definitions within the WFF from their common vernacular use. These core concepts are defined and illustrated in <https://welfarefootprint.org/technical-definitions>.

I. Zootechnical Description

As in any footprinting methodology, the analysis begins with the clear definition of the analytical boundaries and the understanding of the processes and conditions within those boundaries. The Zootechnical Description (module I in Figure 1) fulfills this function by breaking down the complexity of animal lives and production systems into tractable units. It encompasses a hierarchical mapping of the system's living conditions (Species, Production System, Life-Fates, Life-Phases, and Circumstances), while also defining the Species-Specific Needs and establishing the relevant Productivity metrics of the system. The process starts with the definition of the species and breeds. In the case of farmed animals, this is followed by the definition of the Production System(s) to be analysed, whether a specific company or a broader category with established nomenclature, such as an

intensive, pasture-based, multi-tier cage-free aviary, or organic system. These systems often encompass shared sets of key practices, including housing designs, stocking densities, management protocols, and environmental control. For animals outside agricultural contexts, the same principle applies: their living conditions are described in terms of the physical, social, and environmental conditions that determine the animal’s daily environment and experiences.

Because within a production system there are often classes of animals that serve different functions and are exposed to distinct sets of conditions, the goals of the analysis will also dictate the key Life-Fates that must be considered, namely categories of animals with sufficiently distinct life trajectories and experiences (Alonso & Schuck-Paim, 2017). Take for example the production of pork meat in intensive systems. In addition to the pigs slaughtered for their meat (at 5-6 months), there are other Life-Fates involved in the production chain, each exposed to different welfare problems: male breeders, female breeders, and those pigs who die naturally or are culled (hence never experience conditions such as transport or commercial slaughter). For broader analyses, this may also include ‘ancillary species’, such as animals used as feed or for other purposes (e.g., cleaner fish in salmon production).

For each Life-Fate, the relevant Life-Phases (biologically and operationally meaningful stages defined by specific management practices and environmental conditions that shape the animal’s welfare experience) are then identified (e.g., hatching, rearing, growing, transport, slaughter). An analysis may cover the entire lifespan of all Life-Fates, or just specific stages, as illustrated in Figure 2, which covers the commercial slaughter of broiler chickens using electrical waterbath stunning. The figure uses a processogram, or process diagram, a visualization framework designed to convey a time-ordered description of typical phases within the system or life stage of interest, in which the proportions of spatial components are as representative of those in real-life conditions as possible, and fitted along a horizontal axis representing the passage of time.

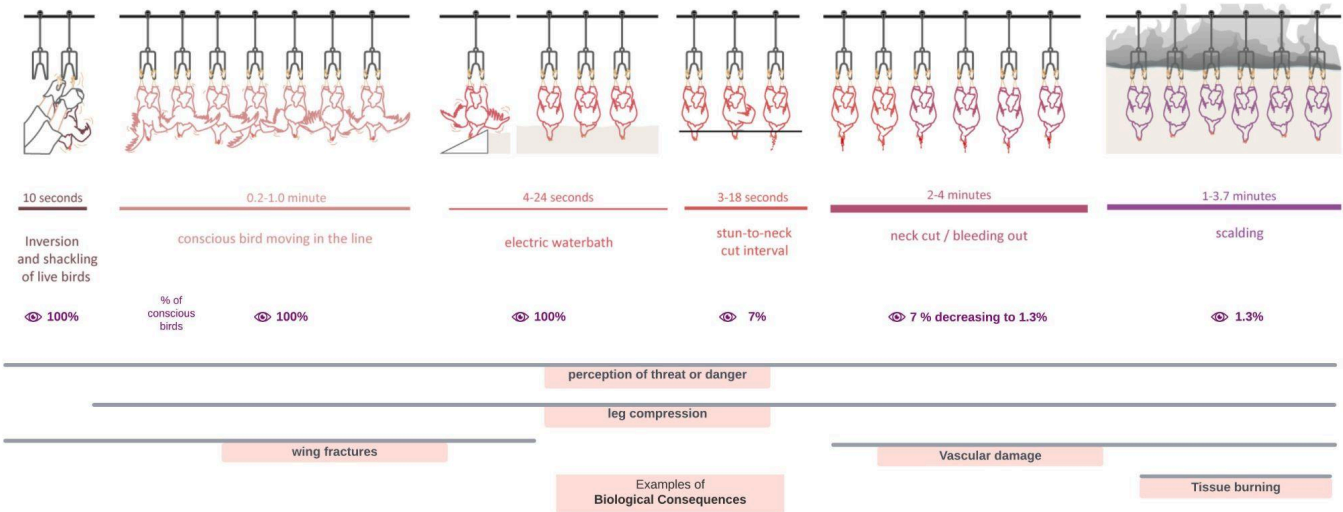


Figure 2. Processogram (process diagram) depicting slaughter of broiler chickens using

electrical waterbath stunning. Sequence and duration of phases from inversion to scalding. Percentages of conscious birds at the onset of each phase are indicated below phase names. Examples of Biological Consequences arising in each phase are mapped beneath the phases.

Within each Life Phase, the external conditions that animals are exposed to, referred to as Circumstances, are then documented. These include housing dimensions and design, group sizes and stocking densities, lighting schedules, availability of key resources, the presence and type of environmental enrichment and the extent to which it provides opportunities for expression of motivated behaviors, feeding regimes, handling and husbandry protocols, procedures such as tail docking, dehorning or beak trimming, as well as the estimated duration of exposure to each relevant Circumstance. Because Circumstances can vary widely in terms of their magnitude of impact, they may be categorized by severity (e.g., moderate, severe, extreme) in terms of deviation from optimal thresholds (e.g., of temperature, humidity, noise, air/water quality variables, stocking densities), infestation load (e.g., for parasites), among others. For example, ammonia has been shown to cause avoidance behaviour and discomfort in laying hens when concentrations exceed ~10 ppm (McKeegan et al., 2005), and welfare effects are worse above 25 ppm, when ocular inflammation and respiratory pathology occur (Miles et al., 2006). Therefore, two groups of Circumstances may be used: exposure to 10–25 ppm ammonia and exposure to >25 ppm ammonia. Disaggregating Circumstances into meaningful groups is recommended when they are likely to lead to different welfare experiences, which can then be properly taken into account in the analysis.

Alongside the hierarchical mapping of living conditions, the Zootechnical Description must formalize the Species-Specific Needs, namely the behavioral, spatial, physiological, and psychological requirements to prevent or reduce the likelihood of negative states (e.g., fear, frustration) and promote well-being (e.g., comfort, agency). A detailed description of Circumstances only becomes meaningful when interpreted in light of these needs (Figure 1), as the interaction between Circumstances and Species-Specific Needs dictates the potential Biological Consequences. Frameworks like the Five Domains Model (Mellor, 2017; Mellor & Beausoleil, 2015) can support the identification of these needs across the domains of nutrition, environment, health, behavior, and mental state.

A careful and representative description of the extent to which needs are met or frustrated in an environment is already highly valuable in itself. In many cases, there is limited clarity about what animals actually experience in a given scenario or production stage: the specific Circumstances they are exposed to, and how they may vary. Even within the same production system or Life Phase, housing, management, and environmental conditions can differ substantially across farms, companies and geographies. For this reason, the Zootechnical Description must also define the geographical scope of analysis, specifying whether the data and estimates are representative of a particular farm, company, region, country, or globally. Finally, the Zootechnical Description also records the Productivity metrics associated with the system (e.g., expected kilograms of meat, liters of milk, or number of eggs per animal). These baseline productivity figures will be utilized in the Econometric Calculation (Module V) to standardize the cumulative affective burdens and express the final Welfare Footprint per unit of output.

II. Veterinary Inventory

The Veterinary Inventory (module II in Figure 1) bridges the gap between the Circumstances animals are exposed to and their consciously experienced affective states. It does so in two steps: (1) by identifying the Biological Consequences (the anatomical, physiological, neurological, perceptual or cognitive changes) that arise from the interaction between an animal's Species-Specific Needs and its Circumstances; and (2) by identifying the Affective Experiences emerging from these Biological Consequences. This cascading structure (Circumstances→Biological Consequences→Affective Experience) is foundational to the WFF, and detailed in this module. Maintaining these distinctions is critical: Circumstances describe external conditions, Biological Consequences the organism's responses, and Affective Experiences are what is consciously felt and therefore the constructs quantified in the framework.

Biological Consequences

Biological Consequences can be physical, encompassing observable bodily effects that impact health or physiological functioning, such as injuries (e.g., fractures, wounds), diseases (e.g., infectious or chronic non-communicable conditions), or physiological imbalances (e.g., dehydration, malnutrition). They can also be perceptual, including the perception of sensorial (e.g., sound, lighting, vibrations), social (e.g., mating opportunities), threatening (e.g., predators) or cognitive (e.g., novelty) stimuli. For example, a hard, abrasive floor (Circumstance) may cause a joint lesion (physical Biological Consequence), while confinement (Circumstance) may result in a perception of lack of agency (perceptual Biological Consequence). It is the extent to which living Circumstances meet or frustrate the Species-Specific Needs that define the potential Biological Consequences. For example, for a breeding sow in a gestation crate, these needs include the motivation to move, explore, build a nest, and interact socially. Confinement prevents these needs from being met, leading to thwarted behaviors and mobility-associated consequences (e.g., lameness, skin ulcers).

Biological Consequences are often multifactorial, resulting from multiple Circumstances. For instance, gastric ulcers in pigs may arise from feed type, irregular feeding, and social stress (Rutherford et al., 2018). These Biological Consequences can cascade, where an initial consequence, such as a fracture (physical), leads to secondary consequences, like undernutrition due to limited food access. Similarly, social isolation (Circumstance) may lead to the perception of the absence of conspecifics (perceptual Biological Consequence), leading to the neurological mechanisms that ultimately generate the affective experience of psychological Pain (such as sadness or distress).

A single Biological Consequence can also manifest in different ways for different individuals, differing in terms of severity (e.g., mild to severe wounds, cancer stages I to IV) and outcome (acute, chronic, and fatal). For example, a urinary tract infection in sows may resolve quickly, persist chronically, or lead to death. Because each has distinct welfare impacts, they must be analysed separately. Severity classifications, such as gait scores for lameness (1–5), body condition scores for nutritional status, wound depth for skin lesions, or extent of inflammation can also capture these differences. Using standardized severity

classifications, such as cancer staging or gait scores, ensures consistency and can facilitate obtaining estimates of the prevalence of these consequences. At the same time, distinctions should not exceed the resolution of available evidence; if population-level data cannot reliably separate conditions by aetiology or symptom, broader severity classes are often the more appropriate unit of analysis.

It is important to emphasize that Biological Consequences are distinct from symptoms, such as lethargy, anorexia, or fever, which are observable clinical signs of an underlying pathology leading to a diagnosis such as pneumonia or gastric ulcers. In some cases, however, well-defined syndromes (sets of symptoms) may be treated as Biological Consequences when identifying the underlying causes is impossible or impractical. Lameness is a primary example. In principle, the burden of pain from lameness could be quantified by estimating how many animals are affected by each possible leg disorder, and then linking the clinical course of each disorder to the corresponding intensity and duration of pain. In practice, however, animals often present multiple skeletal and soft-tissue pathologies simultaneously, correlations between gait abnormalities and specific disorders are weak, and the prevalence of each underlying condition is poorly characterized. For this reason, the literature typically quantifies lameness directly as a syndrome, based on severity of walking impairment (gait score). This enables a more reliable picture of prevalence and permits estimation of pain burdens according to symptom severity, rather than uncertain aetiologies. A similar logic applies to other multifactorial conditions, such as diarrhea in young animals or influenza-like illness in human populations, where diverse causes converge on a common set of clinically observable outcomes

Also, not all Biological Consequences will lead to an Affective Experience; for example, immune suppression or subclinical disease are not consciously experienced, being relevant only if they lead to secondary consequences such as a ‘painful’ infection. These cases illustrate that Biological Consequences may sometimes be intermediate links in the causal chain: they are inventoried not because they are felt, but because they may increase the likelihood or severity of downstream Affective Experiences. This distinction is central to the framework: what has intensity and duration are the Affective Experiences themselves, the constructs that the WFF quantifies.

Finally, the specific links from Circumstances to every Biological Consequence will often not be fully established. For example, even though (the ‘Biological Consequence’) keel bone fractures in egg-laying hens have been studied for decades, the extent to which they are caused by (the ‘Circumstances’) collisions with housing structures, genetics for high productivity, or early laying onset (before the keel bone is fully ossified) is still unclear. Therefore, Biological Consequences can be included in the inventory based on evidence that they occur in the system, even if their precise etiology is not fully understood.

Affective Experiences

Affective Experiences are emotionally felt states, or hedonic experiences, characterized by valence, which may be positive (e.g., joy, satisfaction) or negative (e.g., physical pain, fear), intensity, and duration (Paul & Mendl, 2018). While an Affective Experience represents the complete, dynamic emotional event or episode being evaluated (e.g., the overall experience of tissue damage from tail docking), the specific condition or level of intensity the animal occupies at a given point in time during that experience is

referred to as its Affective State. Intensity captures the subjective magnitude or affective arousal of the experience as it is felt, often inferred through validated behavioral, physiological, and neurological indicators that reflect its influence on the animal's cognitive and motivational priorities, though this may vary in maladaptive conditions such as neuropathic pain where typical signaling mechanisms are altered. These felt states represent the core of animal welfare (Harnad, 2016a), as they reflect what animals consciously perceive.

In the WFF, the term 'Pain' is used operationally for any negative affective experience, namely any state experienced as unpleasant, independently of its origin or brain system involved ([Panksepp 1998; Alonso and Schuck-Paim 2023](#)), such as physical pain, hunger, fear, anxiety, sadness, despair, frustration, boredom and anger (Biro, 2010; Meerwijk & Weiss, 2011). Likewise, the term 'Pleasure' is used operationally for any positive affective experiences (Alonso & Schuck-Paim, 2024a), encompassing both physical Pleasures, such as those emerging from consumption of preferred foods or from sexual intercourse, and psychological Pleasures, such as the positive emotional states emerging from social bonding or maternal care. Both terms are used, operationally, in this broader sense, as outlined in previously published definitions (Alonso & Schuck-Paim, 2023, 2024a).

The relationships between Circumstances, Biological Consequences, and Affective Experiences (Figure 1, Module II) can take several forms, as illustrated in Figure 3. In a one-to-one relationship, a single Circumstance leads to one Biological Consequence and one Affective Experience, such as tail docking causing tissue damage and physical Pain. In a one-to-many relationship, a single Circumstance causes multiple Biological Consequences, such as poor ventilation leading to respiratory infection and thirst. In a many-to-one relationship, multiple Circumstances contribute to one Biological Consequence, such as crowding and poor sanitation causing skin lesions. Many-to-many relationships, common in biological systems, involve multiple Circumstances producing multiple Biological Consequences and Affective Experiences, often synergistically, such as high stocking density, poor ventilation, and high temperatures causing poor air quality, immune suppression, heat stress, respiratory disease, thwarted behaviours and frustration from behavioural deprivation. These complex interactions require careful mapping to avoid "perfectionist paralysis" from overly detailed analyses. Where feasible, Affective Experiences may be described using the notation 'Affective State x' due to 'Biological Consequence(s) y' caused by 'Circumstance(s) z' for clarity.

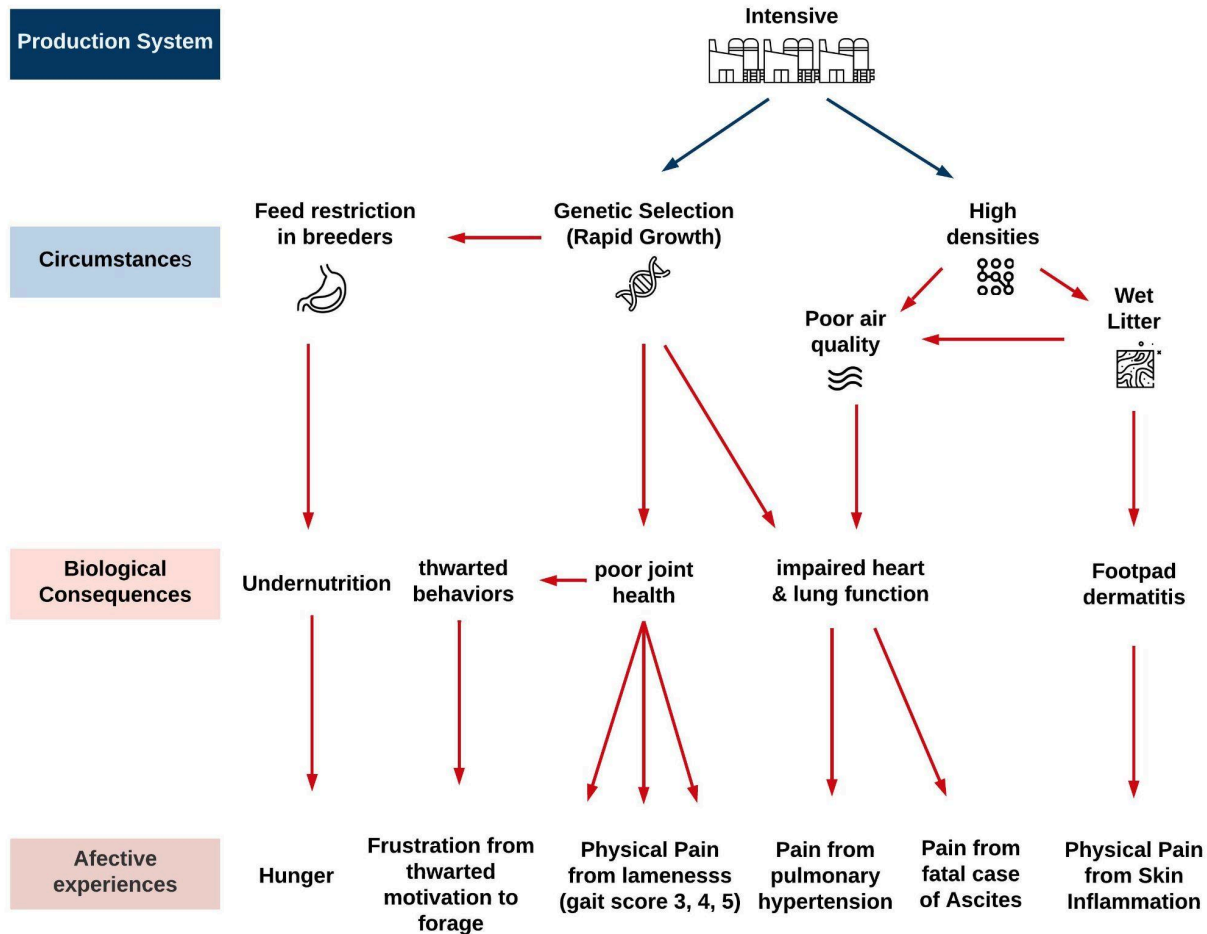


Figure 3. Examples of the Circumstances → Biological Consequences → Affective Experiences cascade in broiler production (examples are non-exhaustive). The diagram illustrates how specific Circumstances (e.g., high stocking densities, wet litter,) interact with species-specific needs to produce Biological Consequences (e.g., undernutrition, poor joint health, impaired heart and lung function). These, in turn, give rise to distinct Affective Experiences (e.g., hunger, frustration, physical pain from lameness, from pulmonary hypertension).

III. Affective Quantification

Affective Quantification is the core analytical process of the WFF, translating evidence about each affective experience into standardized, quantitative estimates of the time an individual spends in affective states of varying intensity. This module employs two complementary tools: Pain-Tracks and Pleasure-Tracks (Figure 4a) for describing hypotheses about the temporal dynamics of negative and positive affective experiences, and Cumulative Pain/Pleasure metrics, which combine the total time spent in each intensity category.

Temporal Description of Affective States: Pain and Pleasure Tracks

The first step involves recognising that affective states are dynamic, evolving over time: Pain may change from intense immediately following tissue damage to a mildly negative sensation associated with chronic inflammation, while Pleasure might progress from lower arousal states to intense experiences during activities like play or positive social bonding. To address this, each Affective Experience is decomposed into meaningful time segments, where each segment is characterized by a relatively stable intensity. Hypotheses about the duration and intensity of the experience, at each segment, are then formalized into standard notation systems (Pain-Tracks for negative states or Pleasure-Tracks for positive states) that enable describing hypotheses about the temporal evolution of affective experiences (Alonso & Schuck-Paim, 2021a, 2024a). In these Tracks, the horizontal axis represents time segments with flexible units (from milliseconds to years), while the vertical axis represents intensity. Durations are expressed in ranges, and intensities in probabilities to reflect uncertainty and biological variation in these parameters (Figure 4a). An example of Pleasure-Track is provided elsewhere (Alonso & Schuck-Paim, 2024a).

(A) Pain-Track		Cutting & Tearing of Tissue	Acute Inflammation	Tissue Healing and Recovery
Excruciating		50%	20%	
Disabling		50%	60%	10%
Hurtful			20%	60%
Annoying				30%
No pain				
Duration:		30s-2 min	2-6 hours	2-7 days
In hours, minus sleep:		0.008-0.033 hrs	2-6 hrs	32-112 hrs

(B) Cumulative Pain		Cutting & Tearing of Tissue	Acute Inflammation	Tissue Healing and Recovery	Cumulative Pain
Excruciating		0.004-0.016 hrs	0.4-1.2 hrs		0.4-1.22 hrs
Disabling		0.004-0.016 hrs	1.2-3.6 hrs	3.2-11.2 hrs	4.4-14.8 hrs
Hurtful			0.4-1.2 hrs	19.2-67.2 hrs	19.6-68.4 hrs
Annoying				9.6-33.6 hrs	9.6-33.6 hrs

Figure 4. Application of the Affective Quantification module to Surgical Castration of Male Piglets. **(A)** Hypotheses about the temporal evolution of pain intensity in surgically castrated piglets without pain relief. Hypotheses are estimated through the integration of the evidence and ratings in Table 1 (section: Case-Study). In the last row, duration ranges are standardized to hours, and sleep time (estimated to average 8 hours) is subtracted as pain is not assumed during sleep; **(B)** Cumulative Pain (in hours), obtained by multiplying the duration of each segment by the probability of each intensity, and summing estimates across segments to determine total Cumulative Pain due to the Affective Experience.

The temporal segmentation is needed not only to ensure that each phase of the experience is internally consistent in intensity but that it can also be appropriately matched to relevant indicators. For example, if pain following fin clipping in fish initially produces vigorous escape attempts and high opercular rates, but later shifts to reduced activity and localized guarding behavior, these two phases would be treated as separate segments, with the intensity of each phase estimated using the appropriate indicators. To avoid arbitrary divisions, segment boundaries should be based on factors that signal genuine changes in perceived intensity, such as underlying biological processes (e.g., a shift from acute tissue damage to an inflammatory repair phase), behavioural transitions (e.g., cessation of escape attempts after capture), or external events (e.g., administration of analgesia). For example, frustration from feed restriction might involve (I) an anticipatory phase characterized by increased arousal and food-seeking behavior, (II) a peak phase during which food is withheld, and (III) a brief resolution phase following feeding, before frustration builds again. Segments may range from very brief to extended periods depending on how rapidly intensity is estimated to change; if intensity remains stable, segments can span longer durations, whereas rapid changes require shorter segments

The next step involves estimating two parameters for each segment: the perceived intensity of the affective state, and its expected duration. To this end, multiple indicators can be used. These may include behavioural patterns (posture, gait, vocalisations, activity levels), physiological measures (heart rate, body temperature, stress hormone concentrations), neurophysiological observations (EEG patterns, evoked potentials), pharmacological responses (changes after administration of analgesics or anxiolytics), immune parameters, anatomical and innervation patterns, as well as evolutionary and logical inferencing (e.g. how important a specific pain signal is to an individual's fitness). Ideally, emphasis should be placed on indicators that most plausibly represent a causal connection with the target affective state. For example, changes in the concentrations of stress hormones are more informative for acute, rather than chronic, stressors, and confounded by many factors, as hormones are released in response to multiple physiological demands unrelated to Pain or Pleasure. Conversely, behaviour and responses to pain-relieving drugs tend to be particularly valuable. This multidisciplinary evidence is evaluated against the definitions of each intensity category (see 'Case-Study' section, and Table 1), treating each category as a testable hypothesis.

The WFF uses four operationally defined intensity categories for each valence: for negative states, Annoying, Hurtful, Disabling, and Excruciating (fully defined at <https://welfarefootprint.org/pain-intensities>); four positive states, Satisfaction, Joy, Euphoria, and Bliss (defined at <https://welfarefootprint.org/pleasure-intensities>). Intensity categories are operationally defined based primarily on the assumption that more intense sensations engage greater attentional resources (Barclay et al., 1988; Eccleston & Crombez, 1999; Mellor et al., 2020; Rowan, 1990; Solms, 2021). This reflects the evolutionary expectation that the greater the threat or reward, the stronger the signal must be to prioritize adaptive responses over competing demands, increasing the odds of survival and reproductive success (Panksepp, 1998; Weary et al., 2009). Both for positive and negative welfare, each intensity level is treated as a hypothesis to be tested against evidence, grounding assessments in empirical observations. While the framework proposes four intensity categories both for Pain and Pleasure, this does not imply an equivalence in their

hedonic weight or in the robustness of the evidence currently available to quantify them (Alonso & Schuck-Paim, 2024a).

Translating Evidence into Probability Estimates

Assessing affective intensity presents a fundamental challenge due to the subjective nature of feelings, which resists direct scientific measurement. This limitation is not unique to the WFF; all welfare assessment methods must confront it. Whether based on behavior, physiology, or expert scoring, all methods assume that observable indicators correlate to some extent with what animals feel, an assumption that cannot yet be fully verified or truly validated. The WFF makes this limitation explicit and manages it by treating each intensity level as a hypothesis to be tested against diverse streams of evidence, including behavioral disruption, analgesic reversibility, physiological and neurological markers, and evolutionary considerations, much like a legal case where the true event is inaccessible and the best estimate emerges from assembling and scrutinizing available evidence.

Each piece of evidence is considered in light of its informative value and causal relevance, and the outcome is expressed not as a single level but as a probability distribution across intensity categories, coupled with ranges for duration. For example, if the available data cannot discriminate between Hurtful and Disabling pain, a 50% probability may be assigned to each, acknowledging uncertainty (from limited or ambiguous evidence) and natural variation (some animals may feel pain or pleasure more intensely, or take longer to recover).

Various approaches can be used to convert evidence into probability estimates, depending on the assessment's goals and the type of data available. In one approach, applied in previous WFF studies (Schuck-Paim, et al., 2025), each piece of evidence is first evaluated for how well it supports or contradicts a given intensity category (Table 1). These ratings are then considered together to assign probabilities to each intensity for a given temporal segment. For example, if the evidence is broadly compatible with both Disabling and Excruciating pain but is stronger for Disabling, a higher probability is assigned to that category. In other cases, evidence may be inconsistent with one intensity but not sufficient to rule it out. For instance, behavioral indicators might be inconsistent with Annoying pain, yet this intensity cannot be excluded entirely, so a small probability is still assigned to it. If evidence is sufficient to rule out some categories altogether (e.g., behavioral and physiological data reject the hypothesis of Disabling and Excruciating pain), probabilities are distributed only among the remaining categories. At the other extreme, in the unlikely case that available evidence provided no basis to distinguish between any categories, even between Annoying and Excruciating pain, probabilities would be distributed equally across all of them, reflecting maximum uncertainty. In general, the stronger and more consistent the evidence for a particular category, the greater the probability it receives. Although the precise figures always involve some judgment (e.g., whether one assigns 50% or 48%), this probabilistic treatment of uncertainty is more rigorous than selecting a single intensity, which effectively assumes 100% certainty for one category and 0% for all others. Box 1 details how subjectivity, inherent to all welfare assessments, is made explicit in the WFF, ensuring that judgments can be scrutinized, replicated, and refined.

Box 1. Subjectivity in the Quantification of Affective States

Since the subjective internal states of non-verbal subjects cannot be directly measured, all animal welfare assessments necessarily rely on indirect evidence (Browning, 2022; Mason & Mendi, 1993). Common proxies include behavior, physiological parameters, brain activity, and responses to pain-relieving drugs.

In practice, expert judgment is central to interpreting these indicators. Experts are typically asked to score constructs such as the severity or intensity of welfare challenges and harms (Honess & Wolfensohn, 2010; Huxley & Whay, 2006; McConnel et al., 2017; Sandøe et al., 2020; Teng et al., 2018; Thomsen et al., 2012; Whay, et al., 2003). For example, EFSA's risk model combines literature reviews with expert elicitation to score the perceived pain and distress caused by welfare consequences. The Welfare Quality® Protocol asks experts to score the severity of different issues on a 0–100 scale, later aggregated into composite indices, while the Five Domains Model grades welfare compromises from A to E based on indirect indicators. In the WFF, the use of indirect evidence in expert-based judgments is structured to make the reasoning path from evidence to conclusion explicit:

1. It recognizes that experiences are dynamic and change over time, allowing evidence to be matched to the appropriate phase of an experience (e.g., pacing may be a strong indicator of frustration during anticipatory feeding but loses diagnostic value once food is delivered).
2. Instead of using arbitrary levels of intensity (e.g., 0-1, 0-100), intensity categories are accompanied by specific criteria for evidence matching: evolutionary, behavioral, cognitive, physiological, pharmacological and immunological. Additional criteria can be incorporated to refine assessments, underscoring the WFF's adaptability.
3. Duration is preserved in its natural dimension rather than scored, a process that can itself add subjectivity.
4. Uncertainty and natural variation in how animals experience conditions are explicitly acknowledged. Rather than assigning a single fixed intensity (e.g., 0–10, A–E, 0–100, 0–1), the WFF represents estimates as probabilities across intensity categories and as ranges for duration.
5. The WFF does not require weighting the relative importance of different welfare criteria (Botreau et al., 2007; Freire & Cowling, 2013; Veissier et al., 2011), a process that introduces subjectivity. Instead, as in evidentiary reasoning in law, evolutionary biology or medical diagnosis, the role of expert judgment is to weigh the relevance and quality of indirect evidence in assigning probabilities. The key is ensuring the link between evidence and outputs is explicit and traceable.

Metrics of Cumulative Affect

Once the temporal segments and their estimated durations, intensity probabilities, and supporting justifications are established in a Pain- or Pleasure-Track, the next step is to estimate the total time the individual spent in each category of affective intensity during that experience. Cumulative Pain refers to the cumulative time spent in each level of negative affect, and Cumulative Pleasure refers to the same for positive affective states.

Cumulative Pain and Pleasure are computed by a straightforward arithmetic operation: for each temporal segment, the duration (often standardized in hours, excluding non-conscious periods like sleep) is multiplied by the probability assigned to each intensity level. Summing these products across all temporal segments yields the total cumulative time the animal is estimated to have spent in each affective intensity as a result of the experience. For example, for the case of surgical castration without pain relief illustrated in Figure 4, this yields 0.4 to 1.22 hours of Excruciating, 4.4-14.8 hours Disabling, 19.6-67.2 hours Hurtful, and 9.6-33.6 hours Annoying pain.

Cumulative Pain and Cumulative Pleasure are highly modular metrics that can be calculated for a single experience, for a Life Phase, lifespan, or any other time interval (e.g. one typical day), as well as standardized across populations or per unit of product. Rather than aggregating these experiences into a single weighted score, the burden of all negative (and positive) experiences at any chosen period is then expressed as the sum of all estimates of Cumulative Pain (or Pleasure), strictly within each intensity category. To ensure transparency and interpretability regarding the analytical level used, these metrics must always be presented with an explicit scope qualifier (e.g., Cumulative Pain [Episode], Cumulative Pleasure [Lifespan], Cumulative Pain [per kg]). This approach mirrors other methods that assume additivity of hedonic experiences (European Parliament, 2010; Honess & Wolfensohn, 2010; Moberg, 1985; Pickard et al., 2013), and is supported by evidence of additive (independent) effects of multiple challenges and stressors on biological functioning, as observed in pigs (Hyun et al., 1998), broilers (McFarlane, et al., 1989) and laying hens (O'Connor et al., 2011). Naturally, biological systems – and sensorial experiences – are more nuanced: the pain from two fractures might not lead to twice the time, or intensity, of one fracture only. We address potential non-additive effects later in this manuscript.

Case Study: surgical castration of young male piglets without pain relief

This case study illustrates how the WFF is used to estimate the burden of the pain resulting from surgical castration in young male piglets, an intervention widely recognized as acutely painful (da Silva et al., 2023; EFSA, 2022; EFSA, 2004; Ison et al., 2016; Marchant-Forde et al., 2009; Prunier et al., 2006, 2019; von Borell et al., 2009), but still used to reduce boar taint (unpleasant odour in the meat of males) and aggressiveness. It is a procedure whereby male piglets are restrained, the scrotum incised with a scalpel, and the testes extracted by either tearing the tissues or severing the spermatic cord. An antiseptic may be then used on the open wound and the piglet is then returned to its pen. Analgesia or anesthesia are typically not administered.

Pain from surgical castration can be segmented into at least three phases: (1) the actual surgical procedure involving the cutting and/or tearing of tissues, which may take anything from 30 seconds to two minutes, depending on dexterity; (2) an acute

inflammatory phase follows in the hours immediately after the procedure, typically 2–5 hours, during which animals show reduced activity, trembling, isolation, abnormal postures, and persistent vocal changes (Castel et al., 2014; Prunier et al., 2006), and (3) a recovery period, when pain gradually subsides, which may last up to seven days, as based on observations of hyperalgesia and increased sensitivity at the wound site for this duration (Castel et al., 2014; Hay et al., 2003), along with frequent pain-related behaviours and evidence of incomplete inflammatory resolution (Table 1). While the recovery phase likely involves a progressive decline in pain intensity, the available evidence is insufficient to define distinct sub-segments, so it is treated as a single phase.

For each temporal segment, pain intensity was inferred by assessing the extent of disruption across behavioural, cognitive, and neurophysiological domains (<https://welfarefootprint.org/pain-intensities>). Disruption serves as the operational marker of pain intensity: the more intense the sensation, the greater its capacity to absorb attention, suppress competing behaviours and other motivational priorities, and require stronger analgesia for relief (Barclay et al., 1988; Eccleston & Crombez, 1999; Mellor et al., 2020; Rowan, 1990; Solms, 2021). Accordingly, Annoying pain elicits little or no disruption of activities, behaviour, cognition, or the possibility of positive welfare, nor major physiological or neurological deviations. Hurtful pain produces partial disruption: motivated behaviours decline, moderate markers of pain appear, and animals may trade work and resources for relief, though typical analgesics are effective. Disabling pain leads to major disruption: activities and positive welfare are largely prevented, attention and cognition are impaired, pain manifestations are evident, and potent drugs are required for relief. Excruciating pain entails complete disruption across all domains and overrides all other priorities: attention is fully monopolised, and even strong analgesics may only attenuate it. Multiple lines of evidence were considered for their consistency with these criteria. Relevant studies were identified by hand-searching the bibliographies of key reviews, excluding those reporting only on analgesia without untreated controls.

Each indicator was evaluated for its consistency with the criteria defining each intensity, summarized in Table 1. Ratings could support an intensity ('consistent'), contradict it ('inconsistent'), leave it unresolved ('unclear'), or in some cases provide grounds to 'reject' it entirely. These ratings were then subjectively integrated to assign probabilities to each intensity within each segment, shown in Figure 4A. For example, during the surgical procedure (segment I), No Pain, Annoying and Hurtful Pain are rejected (Table 1). Because evidence is not sufficient to discriminate between Disabling and Excruciating pain, a 50% probability is attributed to each. In Segment II, No Pain and Annoying pain are rejected. Evidence showing that only morphine is sufficient to suppress pain (Table 1) strongly supports the Disabling intensity. However, Hurtful and Excruciating pain cannot be ruled out by the evidence. A 20% probability is therefore attributed to each, while preserving a greater than 50% probability to Disabling pain. In Segment III, evidence indicates reduced intensity, mostly consistent with Hurtful pain. Disabling pain is unlikely, but cannot be completely rejected, so a small probability (10%) is attributed to it. Hurtful pain is attributed the greatest probability (60%) and the remainder is allocated to Annoying pain (30%). Although the specific probability figures involve subjective estimation (e.g., 60% as opposed to 63, 65 or 70%), this approach is no more subjective than the typical selection of a single intensity (which effectively assigns a 100% probability

to one category only, masking uncertainty). While the estimates remain provisional, they can be updated as new knowledge becomes available.

Table 1: Summary of pain intensity indicators associated with castration of piglets without pain relief during (I) the surgical procedure, (II) the acute inflammatory phase, and (III) healing of tissues. Ratings reflect the extent to which evidence is consistent with the criteria defining the intensity categories (<https://welfarefootprint.org/pain-intensities>): Consistent (+), Unclear (?), Inconsistent (-) and Reject (R). No pain (N), Annoying (A), Hurtful (H), Disabling (D), Excruciating (E). If a category is 'Rejected' by any piece of evidence, the probability attributed to it is 0%.

	Evidence	Intensity				
		N	A	H	D	E
I	Pain-specific manifestations. Calls and screams are longer, of higher frequency and more common in piglets castrated with no analgesia (Kluijvers-Poodt et al., 2012; Marx et al., 2003). Escape attempts are frequent and continuous, but significantly reduced with local or general anaesthetic (Ison et al., 2016).	R	R	R	+	+
	Departures of biological parameters. Sharp and rapid increase in stress markers (e.g., catecholamines, cortisol, ACTH) (Prunier et al., 2006). Marked changes in the electrical activity of the brain (decrease in absolute theta power) (Haga & Ranheim, 2005). Arterial pressure decreases, pulse rate increases (Haga & Ranheim, 2005)	R	-	-	+	+
	Analgesia. Lidocaine and mepivacaine achieved considerable pain relief during skin incision and severing of spermatic cord, but procaine and bupivacaine only effective during severing of spermatic cord (EFSA, 2022)	R	R	-	+	?
	Adaptive Role of Pain. All tissues damaged during surgical castration are highly innervated (European Food Safety Authority (EFSA), 2004)	R	-	?	+	+
	Other evidence. All attention devoted to pain, positive welfare is not possible.	R	R	-	+	+
II	Disruption of activity. Significant reduction in movement, sleeping and nursing, with most individuals reluctant to move for 2.5 h following castration (Hay et al., 2003). For 30 min after castration pigs without pain relief spent more time lying in isolation (Sutherland et al., 2012).	R	R	-	+	-
	Performance of motivated behaviours. Reduction in nursing, activity at the teats, and interaction with littermates and the sow, but no complete interruption.	R	R	?	+	-
	Pain-specific manifestations. Piglets change their posture and protect the affected area (Robles et al., 2023). Multiple pain-specific behaviours, including tail wagging, stiffness, trembling, biting of objects (Hay et al., 2003; Prunier et al., 2006; Robles et al., 2023)	R	-	?	+	+
	Attention and Cognition. Attention to surroundings significantly reduced (Robles et al., 2023). Castrated piglets could navigate a handling chute immediately after castration, but took significantly longer (Bilsborrow et al., 2016).	R	R	-	+	-
	Departures of biological functions. Activation of the protein c-Fos expression [neural marker of pain] after castration, and reduction with local anaesthesia (Prunier et al., 2005). Three times less activated neurons in pigs with local anaesthetic (Prunier et al., 2006); Cortisol, ACTH, lactate significantly higher in castrates 5-120 minutes after castration (Ison et al., 2016; Sutherland et al., 2012). Ear temperature significantly higher for castrates (Ison et al., 2016). Eye temperature, rectal temperature greater at 3 and 5 h post-procedure.	R	-	+	+	+

	Analgesia. Reduction in pain-related behaviours (e.g. prostration, trembling, tail movements, rump scratching, head low, isolation) in piglets receiving meloxicam (Prunier et al., 2019). Local anaesthetics were effective in reducing intraoperative pain, but provided limited peri-operative analgesia (EFSA, 2022). Pain alleviation not effective (e.g., trembling, spasms, scratching, tail wagging, stiffness, facial grimacing) under standard (0.4 mg/kg) or high (1.0 mg/kg) doses of meloxicam, or 6.0 mg/kg ketoprofen (Viscardi & Turner, 2019). Maximal analgesia was achieved only with morphine (1 mg/kg) after surgery (Castel et al., 2014)	R	R	-	+	-
	Adaptive Role of Pain. Pain unlikely to cease immediately after an injury to a highly innervated tissue (European Food Safety Authority (EFSA), 2004). Inflammatory processes likely to occur at the sites of incision (von Borell et al., 2009).	-	-	+	+	+
III	Disruption of activity and maintenance. Castrated piglets are not completely inactive, but are more isolated and desynchronised than shams, 3-5 days following castration (Hay et al., 2003; Llamas Moya et al., 2008; Prunier et al., 2006).	R	-	+	-	R
	Pain-specific manifestations. Tail wagging, rump scratching and huddling are more frequently observed in castrated pigs for five days after castration (Hay et al., 2003). Increased sensitivity to touch at the wound site up to 7 days (Castel et al., 2014; Hay et al., 2003)	R	?	+	?	-
	Analgesia. Piglets receiving meloxicam after castration displayed less pain-related behaviour on both castration day and the following day.	-	-	+	-	-

Figure 4B shows the estimate of Cumulative Pain, representing the burden of physical pain emerging from the procedure. It does not consider the several indirect negative effects of surgical castration, such as increased susceptibility to infections, chronic inflammation, higher pre-weaning mortality and potential long-term neuropathic pain (Prunier et al., 2019). The framework can be used to estimate the loss of welfare emerging from each of these indirect conditions too.

IV. Epidemiological Review

The Epidemiological Review scales individual affective experiences, quantified in terms of intensity and duration, to population-level impacts. Because standard veterinary data typically reports the frequency of diseases or injuries rather than subjective states, this module requires a two-step epidemiological calculation that bridges the occurrence of Biological Consequences with the frequency of the resulting Affective Experiences. We recommend conducting these reviews at the level of Life-Fates to ensure accurate population-level estimates.

First, the WFF evaluates the epidemiology of the Biological Consequence by examining two parameters: prevalence, which represents the proportion of the target population affected by the consequence (e.g., the percentage of a flock with footpad dermatitis), and occurrence, which measures how many times an affected animal typically contracts the condition during the analyzed timeframe.

Second, the WFF evaluates the epidemiology of the Affective Experience. Because a Biological Consequence may be subclinical, continuous, or episodic, the WFF must calculate the Affective Episode Rate, namely the estimated number of discrete affective experiences caused by each occurrence of the Biological Consequence. For

instance, a single chronic joint inflammation (the Biological Consequence) might generate dozens of discrete episodes of physical pain (the Affective Experience) triggered by daily forced movement.

To determine the burden for the 'average population member', the Cumulative Pain or Pleasure of a single affective episode is multiplied by the Affective Episode Rate, the occurrence, and the prevalence. For continuous conditions, the total accumulated duration per occurrence is used directly. For example, 2.5-7.5% of commercial broiler chickens from fast-growing breeds are estimated to suffer from ascites (the abnormal accumulation of fluid in the abdomen). Considering an estimated time in Disabling Pain in individuals affected by ascites of 30-130 hours, the Cumulative Pain [Lifespan] in Disabling Pain due to ascites for the average population member is obtained by multiplying 30-130 by 2.5-7.5% (i.e., ~1-8 hrs of Disabling Pain) (Schuck-Paim & Alonso, 2022).

Prevalences must be estimated for all Biological Consequences in the Veterinary Inventory. Consider for example the process of electrical waterbath stunning for broilers, depicted in Figure 2. It has been estimated that, during inversion, 2 to 5% of birds may experience wing fractures, and 20 to 40% on average will experience pre-stun shocks, even in properly managed systems (Negro-Calduch et al., 2022). Cumulative Pain [Episode] associated with wing fractures and pre-stun shocks must be then multiplied by 0.02-0.05 and 0.2-0.4, respectively, to estimate the population impact of these experiences

Prevalence estimates should be representative of the geographies, production systems, Life-Fates and Life-Phases analyzed, as defined within the analytical boundaries, and should be expressed as ranges to reflect natural variation across subpopulations and epistemic uncertainty from data limitations. Point estimates should be avoided, as they mask true heterogeneity. When direct data are unavailable, estimates should be derived across a defined set of plausible scenarios, spanning from conditions that approach best operational practice to those at the lower end of what is plausible within the system under analysis. Testing whether welfare conclusions hold across this full range, rather than anchoring to a single assumed typical state, is the primary tool for assessing the robustness of estimates to uncertain prevalence inputs

By integrating occurrence and prevalence, the Epidemiological Review establishes the basis for system-wide welfare impacts and welfare footprints. It also reveals welfare distribution patterns, namely whether burdens concentrate in a minority of individuals affected by rarer consequences (e.g., sepsis) and Circumstances (e.g., high-impact events like transport accidents) or are dispersed more homogeneously in the population.

V. Aggregation and Standardization

In this module, population-level estimates of each Affective Experience are summed to determine the total Cumulative Pain and Pleasure for the average member of each Life-Fate. When analyses involve multiple Life-Fate, such as in estimating the welfare footprint of animal-sourced products, Cumulative Pain and Pleasure are aggregated across Life-Fates, weighted by their proportional representation in the population. For example, if there is one female broiler breeder for every 150 broiler chickens, the breeder's welfare burden is distributed across her offspring in that ratio. If the average market chicken endures 50 hours of Disabling pain over her life, and the average female breeder endures

2,000 hours, then the system-wide estimate of Disabling pain per individual is $50 + (2,000 \div 150) \approx 63$ hours.

The framework also enables standardizing estimates by productivity metrics to express Cumulative Pain and Pleasure per unit of output, such as hours of Disabling Pain per kilogram of meat or per liter of milk. For instance, if the average individual in a broiler system experiences 63 hours of Disabling Pain, as calculated before, and yields 2 kilograms of meat per market bird, there will be about 31.5 hours of Disabling Pain per kilogram of meat. Naturally, estimates should account for carcass yield, pre-slaughter mortality as well as losses in the production chain, which effectively reduce the average productivity per animal. Per unit estimates highlight trade-offs in intensive systems, where higher yields may reduce animal numbers, but exacerbate individual burdens.

In the WFF, estimates preserve information from prior modules, enabling tracing welfare impacts to specific sources (e.g., by Life-Fate, Life Phase, or Biological Consequence). This is achieved by maintaining all granular data layers, such as phase-specific Cumulative Pain estimates and prevalence estimates. This traceability supports the identification of dominant contributors to extreme Pain and promoters of Pleasure, and helps inform targeted and effective interventions.

VI. Welfare Footprints: Expression and Notation

This module standardizes the presentation of WFF estimates to ensure interpretability, comparability, and transparency. To this end, estimates must specify the system (e.g., conventional, pasture-based), product (e.g., meat, eggs), species, and unit (e.g., per kilogram, per animal), providing context for the metrics. Cumulative Pain and Pleasure should be expressed in standardized time units and disaggregated by intensity to preserve distinctions between affective states. Furthermore, to ensure interpretability across different analytical levels, the metrics must always be accompanied by an explicit scope qualifier denoting the boundaries of the calculation (e.g., Cumulative Pain [Episode], Cumulative Pain [Lifespan], Cumulative Pleasure [per liter]).

Analytical boundaries must be clearly defined to enable valid comparisons, encompassing the Life-Fates considered (e.g., market animals, breeders), Life-Phases (e.g., rearing, growing slaughter), and Affective Experiences assessed (e.g., Pain from lameness or Pleasure from social bonding). Furthermore, the final notation must explicitly declare the assumption used for simultaneous states, stating whether the Cumulative Affect results are 'strictly additive' or if they have been 'adjusted for concurrent attention effects'." Without this specification, comparisons of estimates from assessments with different scopes, such as one including culled offspring and another excluding them, would be incommensurable, potentially leading to flawed conclusions. Uncertainty can be represented through the inclusion of ranges, distributions or bars, and supporting materials must include Pain- and Pleasure-Tracks, prevalence estimates, and sources (as, for example, in Table 1). This adaptability accommodates diverse applications while preserving rigor, such as simplified summaries for broader use or detailed reports for regulatory purposes.

Ψ. Interspecific Scaling

The analytical modules described thus far are designed for welfare comparisons among individuals of the same species, where it can be reasonably assumed that the capacity for affective experience (or hedonic capacity, the biological potential to experience affective intensity) is broadly similar. This final, and so far optional, module addresses the currently unresolved challenge of interspecific comparisons in hedonic capacity, where that assumption may not hold.

A central reason this problem remains difficult is that two distinct questions are often conflated. The first, and typically most important for welfare conclusions, is a ceiling question about affective intensity: can a given species plausibly reach the upper human-anchored intensity categories, such as Human-Level Excruciating Pain (Excruciating(h)), or is its maximum intensity more plausibly capped at, for instance, Disabling(h) or Hurtful(h)? The second is a time-mapping question: even if two species can reach comparable intensity levels, does one hour spent in a given affective state correspond to the same amount of subjectively experienced duration across taxa? In practice, the ceiling question often dominates, because if a species cannot plausibly reach the most intense human-anchored levels, then many proposed interspecific equivalences become inappropriate regardless of how time perception is modeled.

To reduce ambiguity, the WFF distinguishes between two uses of intensity categories. Unqualified intensity terms (e.g., Annoying, Hurtful, Disabling, Excruciating) refer by default to species-internal categories used to classify time spent in different affective states within that species. By contrast, when making interspecific comparisons, the framework uses explicitly marked human-anchored reference categories [Annoying(h), Hurtful(h), Disabling(h), Excruciating(h)] as absolute calibration points grounded in human phenomenology and functional impairment. This notation is introduced specifically to preserve the integrity of intraspecific Welfare Footprint analyses, while enabling explicit and inspectable interspecific scaling only when such comparisons are required. Human-anchored categories are used as reference levels only; they are not asserted as universal ceilings, and values beyond Excruciating(h) cannot be ruled out in principle, though such claims require especially strong justification.

As with other biological features, it is plausible that variation exists across taxa in both hedonic capacity (Gaffney et al., 2023; Schukraft et al., 2024; Alonso & Schuck-Paim, 2025) and subjective time perception (Schukraft, 2020a, 2020b). Resolving the nature and magnitude of these differences is one of the major open questions in science (Birch, 2024; Feinberg, 2024; Godfrey-Smith, 2016). It is possible, for example, that the maximum intensity of Pain that some organisms can experience is best aligned with Hurtful(h) or Disabling(h) rather than Excruciating(h), while others may be capable of states that exceed typical human reference points (Alonso & Schuck-Paim, 2025). The empirical foundations for such claims remain far from settled (Birch, 2024; Browning & Birch, 2022; Klein & Barron, 2016; Rowan et al., 2021; Visak, 2023).

For this reason, the WFF does not impose a single rigid interspecific assumption. Instead, it provides a flexible and transparent mechanism to accommodate scientific progress and

diverse normative views through optional post-quantification corrections. Importantly, these corrections should prioritize the ceiling question first (i.e., the plausible upper bound of human-anchored intensity a species can reach), and treat subjective time adjustments as secondary and, by default, conservative unless supported by evidence that bears directly on experienced duration rather than on sensory or processing speed alone. In practice, interspecific comparisons are implemented through independent mappings of each species to human-anchored reference levels, rather than through direct species-to-species equivalences.

While the WFF provides the structure to apply such corrections transparently, it cannot at present resolve the deeper challenge of defining a species' welfare range. Until stronger evidence becomes available, any interspecific adjustments, whether based on emerging neurobiological knowledge, explicit ethical weightings, or sensitivity analyses, must be explicitly reported, including the assumptions used to map species-internal intensity categories to human-anchored reference levels.

Normative Flexibility: The Rationale for Disaggregated Intensities

A foundational feature of the metrics of Cumulative Affect is their descriptive nature. The WFF does not aggregate time in different intensity categories into a weighted estimate. While a single measure would be convenient, producing it would require conversion weights. For instance, deciding how many hours of Hurtful pain equal one minute of Excruciating pain, or how long Satisfaction equals a short burst of Bliss. Such knowledge is not yet available. Evidence suggests that affective intensities are valued in non-linear (e.g., the worst Pain or Pleasure may feel many times more intense than the next level down) (Baliki et al., 2009; Cecchi et al., 2012; Gómez-Emilsson, 2019; Stevens, 1957), duration-dependent (e.g., a brief burst of extreme pain or joy may be valued differently from the same state sustained over hours) (Mogensen, 2023) and species-specific ways (insects and mammals may differ in how they weight brief versus prolonged experiences) (Schuck-Paim et al., 2024). Still, consecutive categories can be pooled without such assumptions. For instance, Hurtful, Disabling, and Excruciating can be summed to report time in "moderate-to-intense pain," or Disabling and Excruciating combined as "intense pain." Pooling provides a single measure for calculations or comparisons when needed, while preserving the disaggregated estimates for transparency and detailed analysis.

Similarly, estimates of Pain and Pleasure are not aggregated. The welfare of sentient organisms is shaped by a complex interplay of positive and negative states (Berridge & Kringelbach, 2013; Leknes & Tracey, 2008; Mellor, 2015). However, many are the challenges to compare these states ethically or quantitatively (Harnad, 2016b; Poirier et al., 2019; Reimert et al., 2023; Shriver, 2014; Tomasik, 2015; Vinding, 2020; Yeates, 2018). For example, Shriver (Shriver, 2014) challenges the idea that pleasure and pain are just two ends of a continuum, pointing out that these states are driven by different cognitive processes, contribute very differently to overall well-being, and have separate relationships with motivational systems. Thus, the WFF focuses solely on transparent description, estimating the time in Pain and Pleasure at different intensities.

The WFF's deliberate commitment to providing disaggregated metrics relies on three principles. The first is scientific honesty and transparency. We currently lack an objective, validated method for establishing the numerical relationship between the degree of pleasantness or unpleasantness of different intensity categories. Collapsing them into a single measure would obscure this uncertainty and embed a contestable value judgment within a seemingly objective metric. By keeping the categories separate, no information is lost, and the framework remains transparent.

A second principle is the empowerment of diverse ethical priorities. A disaggregated output allows users to apply their own normative frameworks to estimates. For example, one policymaker might prioritize interventions that eliminate the most extreme forms of suffering, even if they affect few individuals. Another might focus on reducing milder but more widespread suffering, while a third one may focus on promoting positive states. A single measure would make such priority-based decision-making impossible.

Finally, the framework avoids the deep philosophical problem of whether it is valid to equate the intense suffering of a few individuals with the milder suffering of many (Singer, 2015). For example, estimates of Cumulative Pain in a population with individuals enduring intense pain could be similar to that of a population where no individual suffers intense pain, but a larger fraction of individuals experience milder pain for a sufficiently long time. A single aggregate number would mask the ethical distinction between these two scenarios. Likewise, if welfare is measured as a surplus of pleasure over suffering, such a formulation could treat the severe suffering of a few individuals as offset by barely positive welfare experienced by many, effectively allowing others' agony to be "traded off" against unrelated pleasure (Harnad 2016b).

By separating quantification from the ethical evaluation of welfare, the WFF provides a transparent evidence base that serves as a more robust and flexible tool for decision-making. Should a scientific consensus on time-intensity equivalence, and valence compensation, emerge in the future, the disaggregated data provided by the WFF will be readily available for such calculations.

Methodological Strengths

By grounding welfare assessment in cumulative time spent in affective states, the WFF is designed to fulfill a set of properties increasingly recognized as necessary for a universal animal welfare metric.

Affective states represent the defining feature of animal welfare, encompassing the subjective experiences that determine an animal's quality of life (Browning, 2020; Mason & Mendi, 1993; Mellor, 2017; Mellor & Beausoleil, 2015; Reimert et al., 2023). Dimensions such as health, physiological function and opportunities for natural behavior are only important to the extent that they shape affective states, influencing their valence, intensity and duration (Mason & Mendi, 1993b). The WFF directly addresses this core aspect, recognizing that proxies such as mortality, growth performance, or health measures are only part of the measures needed to assess what really matters in terms of welfare: the animal's felt experiences.

The framework's architecture is also built for comparability and scalability. Because it uses a metric with a broadly common biological meaning (time in affective states), it

provides the much needed flexibility to quantify and compare welfare across contexts and over time. The same method can be applied to estimate the welfare burden of a single procedure, the cumulative impact of an entire production system, or the total welfare cost embedded in a product. This also ensures compatibility with life cycle analysis, allowing for a full accounting of welfare impacts from birth to death. Because the framework expresses welfare in units of time, it provides a true ratio scale (Fischer, 2025), meaning that results have a natural zero and can be validly added, compared, and aggregated across experiences and individuals.

The WFF can also incorporate synergistic effects, namely the possibility that Biological Consequences and Affective experiences interact in ways that amplify or modulate affective intensity and duration. For example, early-life trauma may increase an animal's sensitivity to pain later in life. The framework can accommodate such interactions in two main ways. First, because estimates are grounded in behavioural, physiological, neurological, and pharmacological indicators, any interactive effects that are reflected in these indicators will be incorporated automatically (e.g., if a second injury produces more severe disruptions of behaviour and physiology, the model will capture this through higher probabilities to more intense categories in the relevant Track segments). Likewise, if early stressors impair healing, segment durations can be extended based on empirical data of healing times. Second, Pain- and Pleasure-Tracks can be adapted to represent changes in an animal's affective responsiveness. For instance, in prolonged or recurrent experiences, probabilities assigned to later segments can be modified to reflect processes such as sensitisation or habituation. This flexibility enables the WFF to capture complex, long-term welfare impacts more realistically.

The framework is also adaptable; animal welfare science is a relatively new discipline, where data and knowledge gaps abound. For measurement outcomes to remain relevant, flexibility to adjust parameter values in light of new evidence (responsiveness) is critical. In the WFF, all parameters can be revised as new evidence becomes available or stress-tested through sensitivity analysis.

Another strength is transparency. The entire evidentiary pathway from circumstances to affective quantification is explicit, with assumptions, uncertainties and probabilistic estimates documented and preserved through to the final output. This provides an additional advantage: although results are disaggregated solely by valence, intensity, and time, the qualitative distinction of affective experiences remains accessible. For instance, Jaak Panksepp's seminal work (Panksepp, 1998) identified at least three evolutionarily conserved primary negative emotional systems: FEAR (anxiety and escape), RAGE (frustration and competition), and PANIC/SADNESS (social separation distress). In the WFF, estimates can be traced back to these systems (e.g., 'psychological pain due to FEAR during shackling' or 'psychological pain from FRUSTRATION due to thwarted nesting behavior').

This disaggregation also makes it possible to consider cases where multiple affective states occur simultaneously. Animals experience multiple concurrent affective states; for instance, a chicken might endure physical Pain from lameness alongside thermal discomfort and psychological frustration from thwarted behaviors. For most species we do not know how often or when these 'co-morbidities' occur or which combinations are common. But even if comorbidity patterns were known, it is unclear how they should be

treated in welfare estimates: , whether one state cancels out another, whether they should be added in full, or only partly (sub-additively). The WFF offers a foundation for addressing these dynamics. Research suggests that an animal's attention is usually drawn most strongly to the most intense state, which can reduce or block awareness of weaker concurrent states, while states of similar intensity may share attention more homogeneously (Eccleston & Crombez, 1999; Lautenbacher et al., 2007; Schuck-Paim & Alonso, 2024). Incorporating this "attention effect" into Cumulative Affect estimates could improve accuracy by distinguishing between the total time an animal is in a state and the time it is actually aware of that state. This would require reliable data on the magnitude of attention that affective experiences of different intensity demand. Because each affective experience is initially analyzed independently, the WFF defaults to describing each condition using separate Pain- or Pleasure-Tracks, resulting in baseline Cumulative Affect estimates that are strictly additive, and should be interpreted as an unadjusted additive estimate of cumulative welfare burden, before any refinement for concurrent attention effects among co-occurring states. Incorporating the 'attention effect' to account for simultaneous states is treated as an optional, advanced post-quantification refinement. Because applying this effect requires knowing exact comorbidity patterns, which are currently hard to monitor at scale, the framework establishes independent additivity as the practical baseline. By maintaining granular, 'atomized' results, the WFF supports these advanced adjustments when longitudinal data on concurrent conditions become more available. Whatever the choice, the WFF requires explicit notation in the final results of whether estimates are strictly additive or have been adjusted for concurrent attention effects.

Finally, because intensities of Pain and Pleasure, and time itself, are both intuitively understood and biologically grounded, the results are readily interpretable by researchers, policymakers, and the public alike.

Methodological Limitations

As with any welfare assessment tool or scientific approach addressing complex and subjective phenomena, the accuracy and reliability of estimates depend on the availability and quality of evidence to inform the estimates. In the case of welfare assessments, estimates are also constrained by the current state of scientific understanding regarding the emergence and modulation of affective experiences in different species.

One key limitation concerns gaps in the availability, quality, and representativeness of empirical data needed to estimate the intensity and duration of Affective Experiences, as well as the prevalence of the Biological Consequences that give rise to them. Typically, evidence is sparse or even missing for many species. Importantly, the temporal dimension of welfare outcomes has been greatly overlooked in animal research. Little attention has been paid to the onset, duration, and temporal progression of different welfare challenges.. In the case of prevalence data, studies often have limited geographic scope and are conducted under conditions not representative of commercial practice. When evidence is limited, the response is not necessarily to exclude the harm from analysis, since omission is not epistemically neutral: a harm left out of an assessment is effectively assigned a weight of zero. A more informative approach is to represent the uncertainty explicitly, using broad

ranges and/or analyses across plausible scenarios as appropriate, rather than allowing poorly measured harms to disappear from view. In this sense, the WFF aims to make thin evidence visible in the output, while preserving clarity about the degree to which resulting estimates are constrained by data.

Still, a distinct advantage of WFF lies in its granular structure and flexibility to incorporate different types of evidence to inform estimates. For example, by segmenting affective experiences into phases and intensity categories, the framework facilitates the formulation of specific, empirically testable hypotheses (e.g., to what extent pain is experienced at this intensity during the inflammatory stage of the healing process of a small skin wound in this species, pain is experienced at this specific intensity?), which can be addressed through the integration of a wide variety of evidence sources, even logical inference when empirical data is missing. The organization of evidence promoted in the WFF also converts it into a powerful heuristic tool, highlighting where knowledge gaps exist and promoting targeted research where it is most needed.

A difficulty inherent to any welfare assessment is that it is generally harder to evaluate affective states of low arousal, which tend to be less clearly linked to specific events or triggers. An example is mood, often described as a longer-lasting affective state of lower intensity, occurring without a clear cause (Russell, 2003) but rather as the cumulative result of many emotional experiences (Mendl et al., 2010; Nettle & Bateson, 2012; Trimmer et al., 2013). While such states are important for welfare, their diffuse, low-arousal nature means they may be under-represented in quantitative assessments. Similarly, most validated animal-based indicators capture harms (e.g., lesions, disease, imbalances), while indicators of positive states remain scarce (Rault et al., 2025; Rowe & Mullan, 2022; Tuytens et al., 2025). As a result, estimates of positive welfare inevitably carry greater uncertainty. One advantage of the WFF, however, is that by requiring all assumptions and estimates to be made explicit, it highlights these knowledge gaps and provides a transparent structure for targeted improvements.

Application of the WFF also requires detailed system descriptions and expert input, which can limit feasibility in low-data settings. However, this barrier is diminishing: ongoing advances in artificial intelligence can streamline literature review, data extraction, and preliminary affective state estimation (Alonso & Schuck-Paim, 2024b). Emerging automated technologies for on-farm and abattoir monitoring may further enhance feasibility by enabling continuous, automated capture of welfare-relevant data at the individual level ((Gómez et al., 2021; Schillings et al., 2021), but see (Tuytens et al., 2022)). Such systems could provide the much-needed longitudinal data on individual-level welfare, improving understanding of the onset and progression of conditions, their co-occurrence, and associated welfare impacts.

Conclusion

The Welfare Footprint Framework (WFF) provides a structured, evidence-based methodology for quantifying animal welfare through cumulative time spent in affective states, establishing a long sought quantitative and comparable metric that aligns with evolving views of welfare (Reimert et al., 2023) and an increased focus on affective states, their temporal dimension and cumulative effects.

The use of intensity and duration as defining features of affective experience has long been recognized. Risk assessment frameworks such as EFSA's (Bøtner et al., 2012), as well as early cumulative severity models developed for research animals (Conlee et al., 2009; Honess & Wolfensohn, 2010; Hubrecht, 2014) already focused on intensity and duration, with the latter assessing welfare as the accumulation of adverse states over time. The WFF builds on this recognition by creating an evidence-based method for the description and quantification of affective states (Pain-Track and Pleasure-Track), as well as metrics (Cumulative Pain and Cumulative Pleasure) with biological meaning and easy and universal interpretation. This is presented here within a comprehensive framework (the WFF), which allows analyses to be performed up to the level of production systems and units of animal-sourced products, offering societal value by aligning purchasing choices with ethical commitments to animal welfare. This effort builds on decades of animal welfare science, from the Five Freedoms and Five Domains to empirical research identifying key affective states and indicators. The WFF does not replace these contributions but integrates and organizes existing evidence into explicit hypotheses about the magnitude and duration of affective experiences.

WFF metrics support a wide range of scientific, policy, and practical applications. They provide a common, quantitative language for assessing animal welfare, from individual interventions to entire supply chains, making it possible, for example, to identify welfare hotspots, compare the impact of alternative standards or policies or the cost-effectiveness of interventions. Policymakers can predict and track policy impacts, balancing health, sustainability, and welfare goals (Buller et al., 2018; Schuck-Paim et al., 2025b). Certification schemes can apply thresholds of Cumulative Pain and Pleasure to validate standards and facilitate comparison across schemes (Butterworth & Kjaernes, 2007). For consumers, the framework translates abstract welfare concerns into relatable information, empowering choices aligned with personal values. This is particularly important given strong public interest in the ethics of animal food production—an interest not yet reflected in the market share of higher welfare products (Tuytens et al., 2025; Vanhonacker & Verbeke, 2014). Beyond food production, the same approach can be applied to wild animal welfare, research and testing contexts, working and companion animals, and sentience research, enabling systematic comparison of welfare impacts across species, settings, and purposes.

Like other welfare metrics, the WFF relies on indirect proxies for the assessment of subjective experiences and provisional assumptions in interspecific scaling, which await refinement through progress in affective neuroscience and comparative biology. Its modular architecture, however, allows adaptability, including potential synergies with technologies such as precision farming and artificial intelligence.

To advance its development into a robust and widely applicable tool, a structured roadmap is in place. This includes establishing an open-source repository of Pain- and Pleasure-Tracks, developing welfare footprints of animal-sourced products, evaluating the cost-effectiveness of welfare interventions, and encouraging independent research. This collaborative effort aims to build a comprehensive evidence base, inviting the empirical scrutiny and iterative improvement needed to further the study of animal experience.

By making its assumptions explicit and preserving qualitative detail alongside quantitative outputs, the WFF establishes a transparent foundation for research and ethical

debate. As new data emerge and methodologies advance, the framework can incorporate species-specific scaling, rely on a richer set of indicators to inform positive welfare estimates, and include finer-grained affective distinctions, enhancing its role as a decision-support tool for ethically informed policy and practice.

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Competing Interests

The authors declare no competing interests.

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