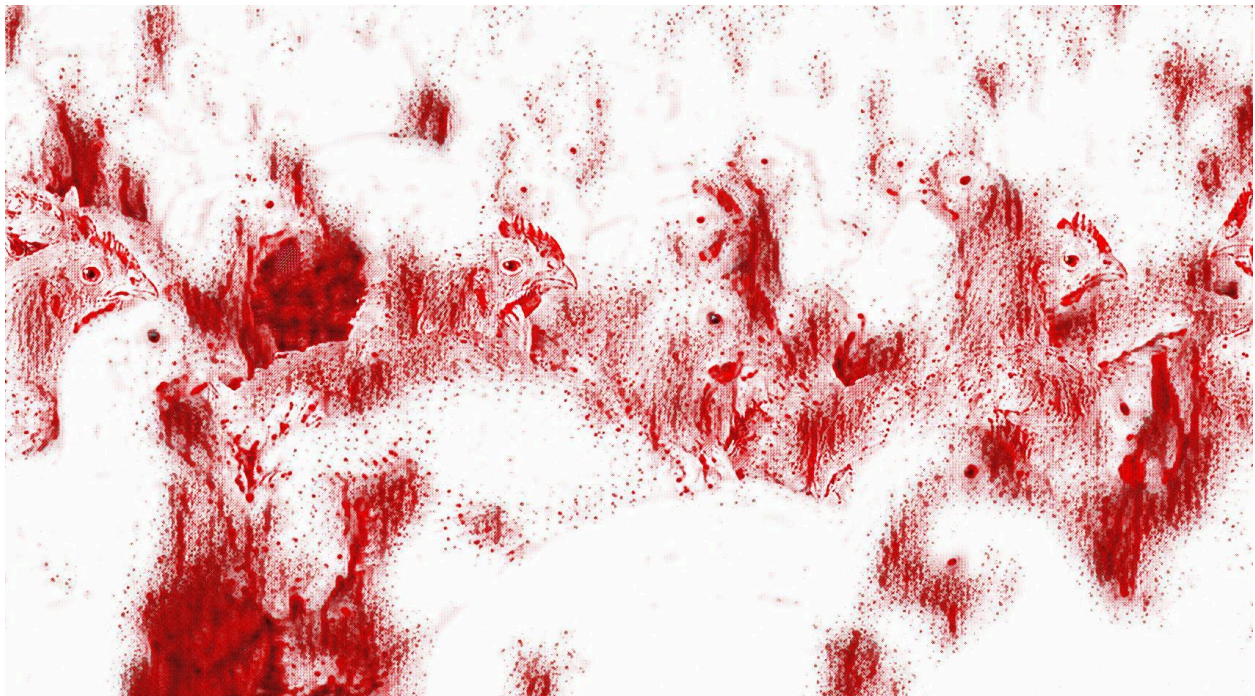

The welfare impact of heat stress in modern breeds of broiler chickens

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I. Background

Heat stress is widely regarded as a major challenge for the poultry industry. In the United States, production losses due to heat stress were of the order of \$128 to \$165 million annually in 2003 [1]. In tropical and subtropical countries the impact of the problem is likely to be higher [2].

Importantly, heat stress is a major source of poor welfare, causing suffering and death to millions of birds every year. All metabolic processes (including the frenetic rate of cell division in modern breeds of fast growing broilers) involve the oxidation of metabolic fuels (chiefly carbohydrates and fats), which generate substantial amounts of heat. Heat stress occurs when the amount of heat produced by an animal surpasses its capacity to dissipate it to the environment, as a result of both environmental factors (e.g. high temperatures, humidity, poor ventilation, stocking density) and the animal's traits (e.g. body size, body surfaces' sizes, their thermal resistance, metabolic rate, coping mechanisms) [3].

Although birds are homeotherms (they are able to maintain their body temperature within an appropriate range under normal circumstances), multiple factors can compromise their ability to thermoregulate. Poor ventilation, high temperatures and high humidity all contribute to heat stress. The possibility to lose body heat through convection (whereby heat is lost to cooler air surrounding the bird) and by adjusting posture (e.g., by lifting their wings away from the body or moving away from other birds) is also compromised at high stocking densities. Despite the use of automated control systems for the regulation of parameters such as temperature and ventilation in many poultry houses, stocking densities of around 39-42 kg per square meter, which are typical in commercial settings, can make it very difficult for ventilation systems to clear out hot air from around the birds' bodies [4,5]. Additionally, fast-growing strains of birds are at high risk of experiencing heat stress, as increased feed consumption leads to high feed-induced thermogenesis, with a higher metabolic rate further increasing the production of body heat [6–9].

One of the first visible signs of heat stress is panting. Since birds do not have sweat glands, they evolved other mechanisms to keep their temperature from rising. Panting is one important means whereby excessive heat is dissipated through evaporation of the air from the respiratory tract [10]. Although panting can be sustained for long periods of time, when air moisture levels are high, expelling out the air becomes harder. To compensate, breathing rates can increase by as much as 10 times the rate during resting [11]. Rapid breathing, which consumes a lot of energy, can tire the animals and produce more heat, further reducing their ability to cope with extended periods of heat stress [11]. Other behavioral changes commonly associated with heat stress include wing spreading, squatting close to the ground, drinking, sleeping, dozing, and sitting [12]. Birds will also reduce the amount of time spent eating, standing, and walking [12]. In addition, birds may be found lying prostrate in an attempt to increase heat loss to the litter [13]. High temperatures, restricted movement and excessive panting can also lead to dehydration. Although under normal environmental conditions chickens can sustain extended periods of time without water, dehydration is substantially increased by heat stress.

Heat stress also triggers several physiological and metabolic processes that aim to cool the body, but which can negatively affect the bird in multiple ways. To help the animal cool down, blood flow is diverted from the liver, kidneys and intestines to blood vessels in the skin. Intestine motility and digestion slows-down and feed intake is reduced, increasing the risk of digestive disorders. Increased

cellular energy demand for thermoregulation also promotes the appearance of reactive forms of oxygen in high quantities, leading to oxidative stress [14–16]. Heat stress also activates the hypothalamic-pituitary-adrenal (HPA) axis and the sympathetic-adrenal-medullar (SAM) axis, which promote the release of glucocorticoids, vasodilation, lipolysis, and proteolysis in muscles [17]. Stress hormones, including plasma corticosterone, are elevated [18,19], as is the activity of hepatic enzymes (aspartate transaminase, alanine transaminase), suggesting liver damage [20,21]. Serum levels of heat shock proteins (a protective mechanism against different forms of stress) are also increased [12]. Heat stress's impact on physiological and metabolic processes is also apparent post-mortem, with accelerated glycolytic metabolism causing meat that is pale and exudative [22–24]. The immunosuppressive effects resulting from heat stress and the cascade of physiological reactions it triggers are similarly well established, and include higher heterophil:lymphocyte ratios, reduced thymus, spleen, bursa, liver and lymphoid organ weights, reduced antibody responses, lower specific IgM and IgG levels during primary and secondary humoral responses and a hindered phagocytic ability of the macrophages [18,25].

In this chapter we seek to quantify the impact of heat stress on the welfare of fast- and slower-growing birds using the Cumulative Pain Framework [27]. We focus on two scenarios: one where broilers reach a slaughter weight of 2.55 Kg in 6 weeks, and another where slower-growing birds take 8 weights to reach the same weight (see Chapter 1 for a justification). We start by investigating the extent to which heat stress affects individuals in commercial flocks.

II. Prevalence of birds affected by heat stress during production

One way to investigate the extent to which heat stress impacts broiler flocks would be by examining estimates on the economic losses incurred by the poultry industry as a result of heat stress. In possibly what has been the most comprehensive modeling study in this area, the authors estimated the effects of heat stress by calculating, for each state in the United States, a daily temperature-humidity index from weather data, to then determine the extent to which these indexes were above the maximum threshold of thermal comfort that broilers can normally withstand [1]. The authors concluded that, nationally, the average broiler was exposed to conditions of heat stress in about 8% of all annual hours, from no time in states like Wisconsin and Minnesota, to nearly 17% of the time in states like Florida and Texas [1]. It is however difficult to determine the extent to which these climatic measurements, obtained from weather stations, can capture the microclimate conditions actually experienced by birds inside poultry houses. For example, temperature at bird height can be much higher than temperatures measured at human height [44]. Additionally, stocking density and the design of the house will affect the likelihood of exposure to heat stress. For example, in a study that compared broilers from Belgium and Brazil [28], panting scores were better for Brazilian birds, even though average temperatures in Brazil are much higher than those in Belgium. The authors suggest that the lower proportion of birds panting was possibly a combination of the lower stocking density in conjunction with the open-sided design of housing units—which allowed natural ventilation— in Brazil.

Another possible approach is to investigate the extent to which poultry houses adhere to the recommended ranges of temperature and humidity for each age and stocking density to avoid heat

stress. Table 1 illustrates recommended temperature ranges at several stocking densities for the fast-growing Cobb breed in a controlled environment [29]. In warmer climates and in houses lacking fully automated ventilation systems, lower stocking densities are usually recommended (eg, 20-30 kg/m²) to avoid heat stress [30].

Table 1. Recommended temperatures for fast-growing broilers raised in controlled environments at different stocking densities [30]. Stocking densities typical in commercial settings are of around 39-42 Kg/m²

Density (Kg/m ²)	Temperature Range (°C)
28	22-24
30	21-23
32	20-22
34	19-21
36	18-20
38	17-19
40	16-18
42	15-17
>42	14-16

Still, this approach is limited in that very little data has been published [4,31] on environmental parameters, by age or density, in commercial broiler houses to enable a generalization of the incidence of heat stress to the entire poultry industry. Another major constraint is the high likelihood of underestimating the prevalence or time of exposure to heat stress. Even if house temperature is controlled and within recommended limits, heat stress is still likely to occur under several circumstances. For example, when stocking densities increase above 28 Kg/m², heat trapped below the birds can build up very quickly, requiring stockmen to constantly monitor bird behavior, feed and water intake, air velocity and other variables to make sure birds are thermally comfortable [29]. Similarly, relative humidity levels above 70% will make it very difficult for birds to thermoregulate regardless of adequate ventilation and temperature, yet reporting of humidity levels does not seem to be current commercial practice [4]. Importantly, environmental parameters measured at the house level are likely to miss important spatial variations in the microclimatic conditions experienced by birds within the various sectors of the house. Several studies have shown an uneven spatial distribution of environmental variables (air and litter temperature, humidity) inside broiler houses, which are often accompanied by spatial variations in the skin temperature of birds and the likelihood of severe outcomes of heat stress [32,33].

We have therefore opted for directly analysing animal-based indicators of heat stress in commercial poultry houses. Specifically, we look at reports on the proportion of birds panting, a reliable indicator of thermal discomfort widely used in poultry welfare research, including welfare assessment such as the Welfare Quality Protocol [34]. In a study conducted with fast-growing strains in 11 commercial flocks in Brazil and 11 commercial flocks in Belgium [33], the authors report a median of 33% (3-59%) and 46% (7-96%) birds, respectively in the Brazilian and Belgian flocks panting by the end of the production cycle. In another study involving 139 commercial flocks in Europe, the mean proportion of birds panting by the end of production was approximately 10% in fast-growing birds, and 2% in

slower-growing strains [34]. A similar range (approximately 10-30%, As inferred based on the reporting of a welfare score of 69 [32]) was reported in China for fast-growing strains [35].

Based on these findings, we tentatively assume that an average proportion of 10 to 40% of birds within a typical flock of fast-growing broilers, growing near the maximum allowed density for the housing type used (close or open-sided), will be affected by heat stress in the last week of the 6-weeks growth cycle. We conservatively assume that no birds will be affected by heat stress in the first two weeks of life (given their small body size and lower thermal resistance, young chicks are more vulnerable to cold conditions). On weeks 3 and 4, we consider an intermediate prevalence between the first and the last week. We also assume that the widely used practice of partial depopulation, referred to as “thinning” of the flock, is performed between weeks 5 and 6 of age. Thinning allows producers to increase production at a lower fixed cost while staying within the legal stocking density requirements by selectively removing portions of the flock at one or more time points within the rearing period. Typically, birds considered ‘less efficient’ are selected and sold to markets that prefer lighter birds, such as the fast-food service. Grocery services typically prefer mid-weight broilers, and the largest weight birds that remain at the end of the rearing period typically go to further processing. Here, a slightly lower frequency of birds is assumed to be affected by heat stress on Week 5 compared to Week 6 given the temporary reduction in stocking density during this week as a result of thinning (it is typical for 25 to 30% of a flock to be removed at thinning [37]). Table 2 summarizes these assumptions.

These estimates are likely conservative in that they focus only on the effects of chronic heat stress, characterized by the experience of high temperatures for a longer duration. Episodes of acute heat stress, namely the experience of intense environmental temperature for a brief period, are unlikely to have been captured in the previously mentioned welfare assessments [28,35,36], from which the proportion of birds panting by the end of production was estimated.

The estimates assume that the likelihood of heat stress increases across the rearing period [38]. As the birds grow, they progressively fill up more and more of the floor space. Near the end of production, bird bodies may take up nearly all floor space within the barn, impeding heat transfer from the surface of the litter [39]. As the birds age, they also tend to spend increasingly longer times lying in the litter, further increasing litter temperature (litter temperature in flocks at 6 weeks of age has been shown to be about 1.5 degrees Celsius higher than at lower flock densities [40]). High stocking densities also contribute to an increased production of feces, which increases the moisture and nitrogen content in the litter. This can increase microbial activity in the litter, in turn leading to the production of more heat and ammonia [39]. Heat dissipation also becomes progressively more difficult as stocking density increases due to the increasingly higher levels of humidity in the house.

Slower-growing strains are known to be less susceptible to heat stress [41–43] than their fast-growing counterparts. Additionally, their slower metabolism means that the heat produced by their bodies is lower than fast-growing strains. Accordingly, research has shown that slower growing strains have better growth rates and feed conversion than fast-growing strains in similarly high thermal conditions, further suggesting that these birds are less likely to experience discomfort from heat stress across the rearing period [44]. Here, we consider observations that the prevalence of birds panting in slower-growing flocks tends to be five to six times lower than in fast-growing flocks [35,45] (Table 2). For example, we assume that 1-5% of slower-growing birds are typically affected in weeks 3 and 4, and 2 to 10% of birds are affected by heat stress in weeks 5 and 6, increasing linearly

subsequently, consistent with the idea that at higher stocking densities heat stress might also be a welfare concern for slower-growing birds [46].

Table 2. Assumptions regarding the expected prevalence of birds within commercial broiler flocks affected by heat stress in four varieties of breeds, as based on observations of the proportion of birds panting at the end of the production cycle in different countries (Europe, China, Brazil).

Breeds	Age in Weeks							
	1	2	3	4	5	6	7	8
Fast-growing	0%	0%	2%-10%	3%-15%	6%-25%	10%-40%		
Slower-growing	0%	0%	0.5%-3%	0.5%-3%	1%-6%	1%-6%	2%-10%	2%-10%

III. Pain-Tracks

In this section we investigate the possible intensity, and duration, of the non-fatal negative states associated with heat stress in fast- and slower-growing breeds. Given the natural cycle of diurnal air temperature variation, in all scenarios we conservatively assume that, regardless of stocking density and ventilation system, no negative affective state (discomfort) as a result of heat stress is experienced during the cooler times of the day, which may vary from 12 to 16 hours depending on season, latitude and altitude of commercial operations. Daily exposure to heat stress was therefore estimated to last from 8 to 12 hours. For both scenarios, the rationale underlying the attribution of intensity associated with heat stress (Box 1) in each week are described next.

Box 1 Definition of Pain Intensity Categories

Annoying: experiences of pain perceived as aversive, but not intense enough to disrupt the animal's routine in a way that alters adaptive functioning or affects the behaviours that animals are motivated to perform. Similarly, Annoying pain should not deter individuals from enjoying pleasant experiences with no short-term function (e.g., play) and positive social interactions. Sufferers can ignore this sensation most of the time. Performance of cognitive tasks demanding attention are either not affected or only mildly affected. Physiological departures from expected baseline values are not expected to be present. Vocalizations and other overt expressions of pain should not be observed.

Hurtful: experiences in this category disrupt the ability of individuals to function optimally. Different from Annoying pain, the ability to draw attention away from the sensation of pain is reduced: awareness of pain is likely to be present most of the time, interspersed by brief periods during which pain can be ignored depending on the level of distraction provided by other activities. Individuals can still conduct routine activities that are important in the short-term (e.g. eating, foraging) and perform cognitively demanding tasks, but an impairment in their ability or motivation to do so is likely to be observed. Although animals may still engage in behaviors they are strongly motivated to perform (i.e., exploratory, comfort, sexual, and maintenance behaviors), their frequency or duration is likely to be reduced. Engagement in positive activities with no immediate benefits (e.g., play in piglets, dustbathing in chickens) is not expected. Reduced alertness and inattention to ongoing stimuli may be present. The effect of (effective) drugs (e.g., analgesics if pain is **Disabling**: pain at this level takes priority over most bids for behavioral execution, and prevents all forms of enjoyment or positive welfare. Pain is continuously distressing. Individuals affected by harms in this category often change their activity levels drastically (the degree of disruption in the ability of an organism to function optimally should not be confused with the overt expression of pain behaviors, which is less likely in prey species). Inattention and unresponsiveness to milder forms of pain or other ongoing stimuli and surroundings is likely to be observed. Relief often requires higher drug dosages or more powerful drugs. The term Disabling refers to the disability caused by 'pain', not to any structural disability.

Excruciating: all conditions and events associated with extreme levels of pain that are not normally tolerated even if only for a few seconds. In humans, it would mark the threshold of pain under which many people choose to take their life rather than endure the pain. This is the case, for example, of scalding and severe burning events. Behavioral patterns associated with experiences in this category may include loud screaming, involuntary shaking, extreme muscle tension or extreme restlessness. Another criterion is the manifestation of behaviors that individuals would strongly refrain from displaying under normal circumstances, as they threaten body integrity (e.g. running into hazardous areas or exposing oneself to sources of danger, such as predators, as a result of pain or of attempts to alleviate it). The attribution of conditions to this level must therefore be done cautiously. Concealment of pain is not possible.

Pain Intensity Attribution

Panting, a reliable indicator of thermal stress, is normally expected to occur when the ambient temperature is near or above 30°C. At this stage, broilers will substantially decrease their level of activity (compared to broilers of the same age not exposed to heat stress) and reduce feed intake [47]. This challenge is highly unlikely to be of an Annoying nature only, as it changes behavior and cannot be ignored for most of the time - criteria needed for a match with this intensity level (see intensity definitions in Chapter 1). Still, lighter birds in less dense, or better ventilated, sectors of the house may not be affected by heat stress to the same extent as the average flock member. Therefore, we consider the possibility that for a fraction of individuals the level of distress experienced is only of an Annoying nature.

Considering the limited ability of birds to effectively dissipate heat, prolonged exposure to heat stress can be fatal, for example by leading to heat exhaustion and stroke. Above 38°C high mortality is often observed [48]. The severity of the effects of heat stress and the likelihood of death from heat exhaustion is higher in older and heavier birds [49], as body temperature increases with age and size along with a reduction in the ability to dissipate heat, independently of the environmental temperature [48]. While for 1 week old chicks the thermoneutral temperature ranges from 31 to 33°C

(when relative air humidity is 65-70%), this range drops to 21-23°C between 5 and 6 weeks of age [48]. Accordingly, daily mortality from heat stress is also highest at the end of the rearing period, near marketing time, when stocking densities are the greatest [50].

Given the costly nature of heat stress for survival and reproduction, from an evolutionary perspective heat stress is expected to be associated with effective signals of thermal discomfort, possibly similar in intensity to those associated with thirst. From a behavioral perspective, the observation that heat stress changes behavior, appetite (or willingness to seek food) and leads to prostration levels that can in some cases make birds adopt highly unnatural behaviors (for this species), such as a lateral decubitus position [47], is also consistent with a more severe level of pain. Likewise, stress hormone levels, such as corticosterone, are also substantially elevated in broilers exposed to heat stress [18,19], as are the levels of other biomarkers of physiological stress (reviewed in the Background Section).

Therefore, we distribute the remaining probabilities between the Hurtful and Disabling categories. Since walking, eating and drinking is often impaired by heat stress, but not completely suppressed, a greater likelihood is attributed to the Hurtful category. For some birds, however, it is not possible to rule out the possibility that discomfort reaches a Disabling level of pain (particularly for those individuals in densely packed sectors of the house, or where ventilation is less effective). The likelihood that heat stress is of a Disabling nature increases together with age, size and stocking density, given the diminished ability to dissipate heat, the lower range of temperature in the thermoneutral zone, and the fact that evaporative heat loss through panting becomes increasingly ineffective due to higher relative air humidity that typically accompanies higher stocking densities. If birds become severely dehydrated, there may be symptoms of disorientation and seizures (in humans, neurological signs, consisting of lethargy, weakness and confusion appear with great losses (>10%) of body water [51]). For fast-growing birds, on Week 5, following ‘thinning’, density is reduced and so is relative air humidity, increasing the ability of the birds to dissipate heat through panting. In Week 6, with the increase in density, thermal discomfort is assumed to become as severe as prior to thinning.

Scenario 1: fast-growing broilers

Pain-Track 1 describes the proposed hypotheses for the intensity and duration of the pain associated with heat stress. To this end, we consider specifically the case of a bird panting. Values represent the level of discomfort in such a situation, for each week of a production cycle of 42 days. Time estimates assume that, on average, birds are only 8-12 hours awake per day, and that no discomfort from heat stress occurs while the bird is asleep (see Chapter 1, for a detailed justification).

Pain-Track 1. Hypothesis for the intensity and duration of the pain endured per day by commercial fast-growing broilers **affected** by heat stress. The duration considers hours awake, and that no discomfort from thermal stress

occurs while the bird is asleep. The table on the right shows the total time in pain (hours) endured by affected individuals in each intensity category over the entire production cycle.

	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6		TIME IN PAIN (h)
Excruciating							Excruciating	
Disabling			15%	20%	15%	20%	Disabling	49 [39-59]
Hurtful			70%	70%	70%	70%	Hurtful	196 [158-235]
Annoying			15%	10%	15%	10%	Annoying	35 [28-42]
	56-84 h	56-84 h	56-84 h	56-84 h	56-84 h	56-84 h		

Scenario 2: slower-growing broilers

Pain-track 2 illustrates the hypothesized discomfort experienced by slower-growing broiler genotypes affected by heat stress across the rearing period, assuming a single thinning procedure is carried out at around 6 weeks of age [52].

The same rationale as that used for the attribution of intensity in Pain-Track 1 is applied here. The expectation that slower-growing birds are more resilient to heat stress is reflected in the lower estimated prevalence of the typical number of birds affected within flocks (Table 2). However, for those birds that 'are' affected, comparable levels of thermal discomfort are expected for birds of the same size kept at the same density (both slower-growing and fast-growing strains have elevated corticosterone levels during periods of heat stress [16]). For example, levels of distress for slower-growing strains reaching a slaughter weight of 2.5 Kg at 8 weeks (Pain-track 2) are assumed to be comparable to those experienced by fast-growing individuals reaching the same weight at 6 weeks (Pain-Track 1). Likewise, at approximately 5 weeks slower-growing birds under heat stress are estimated to have a similar experience as fast-growing individuals aged approximately 3 weeks (Pain-Track 1). Here, too, increasing intensities of discomfort are assumed over the production cycle, as stocking densities progressively increase. However, the rate of increase in discomfort is lower, since stocking density increases at a lower pace.

Pain-Track 2. Hypothesis for the intensity and duration of the pain endured per day by slower-growing commercial broilers **affected** by heat stress in slower-growing breeds kept to 8 weeks in indoor housing systems). The duration considers hours awake, and that no discomfort from thermal stress occurs while the bird is asleep. The table on the

right shows the total time in pain (hours) endured by affected individuals in each intensity category over the entire production cycle.

	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8		TIME IN PAIN
Excruciating									Excruciating	
Disabling			5%	10%	10%	15%	15%	20%	Disabling	41 [33-49]
Hurtful			70%	70%	70%	70%	70%	70%	Hurtful	235 [196-274]
Annoying			25%	20%	20%	15%	15%	10%	Annoying	59 [50-67]
	56-84 h	56-84 h	56-84 h	56-84 h	56-84 h	56-84 h	56-84 h	56-84 h		

IV. The burden of pain from thermal stress in broilers

Figure 1 shows the estimated time endured at each level of pain intensity by an “average” fast- and slower-growing broiler chicken (see Box 2 for a definition). In this case, the times in pain at each intensity level endured by birds are weighted by the estimated proportion of birds affected by heat stress, as shown in Table 2. Thus, times are shorter than those shown on the right hand side of Pain-Tracks 1 and 2, since most individuals are not expected to suffer from heat stress during production.

Box 2 Time in Pain endured by the Average Population Member

Although pain inherently concerns individuals, we operationally accept that the collective welfare of the members of a population can also be determined. Measuring cumulative pain at the population level is also necessary to account for the heterogeneity in the exposure of population members to different challenges. For example, while lameness is experienced by a large fraction of broiler chickens (Chapter 2), events such as fatal cases of ascites are only experienced by a few individuals.

Therefore, measurement efforts must consider the prevalence of each welfare challenge, so that pain is determined for the average member of the population (which may not necessarily correspond to any real organism). At the population level, the time spent at each level of pain intensity as a result of each challenge is determined by multiplying it by its prevalence. For example, if a condition causes 10 hours of Disabling pain and 70% of the population are affected, then the average member of this population could be said to experience 7 hours of Disabling pain due to the condition. Measurements at the population level enable comparing the impact of different practices and conditions across demographics, geographies and time.

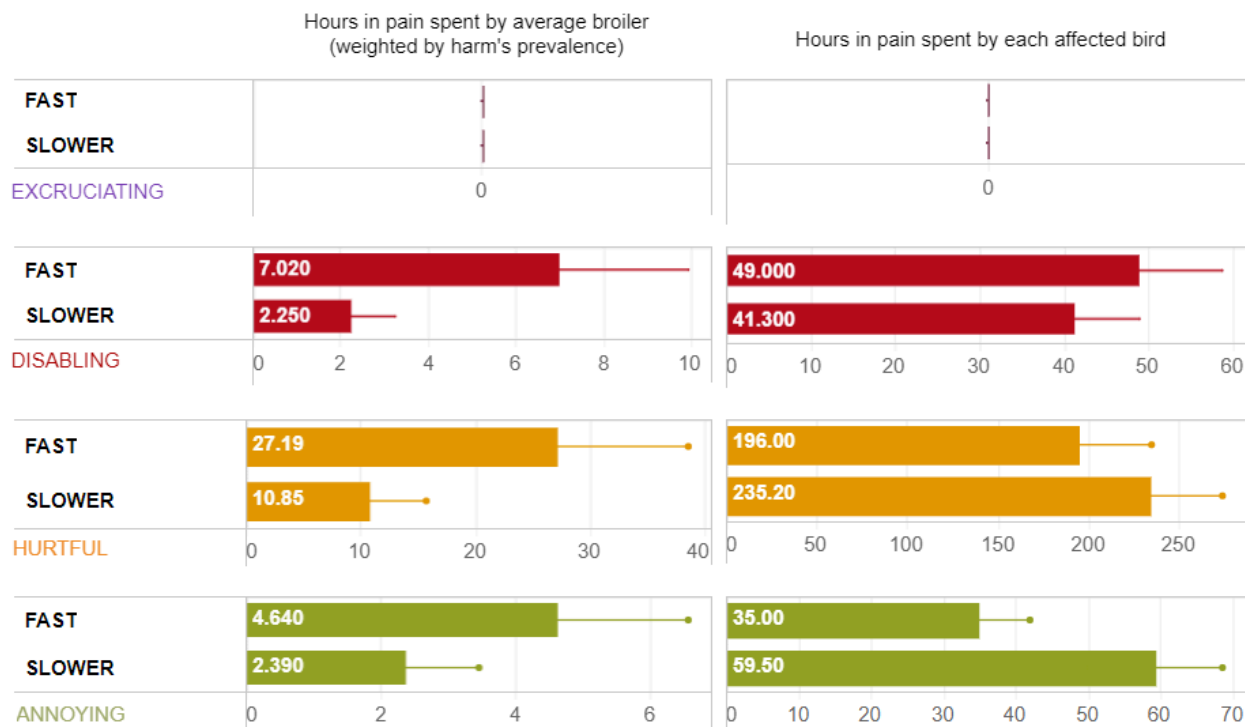


Figure 1. Total time endured at each level of pain intensity (hours) by an “average” broiler chicken as a result of heat stress. The results assume the average global proportion of birds affected by heat stress as shown in Table 2. Error bars represent uncertainty intervals. An interactive version of the figure is available at <https://welfarefootprint.org/broilers/>.

The impact of heat stress on welfare loss in fast-growing birds is lower than that estimated for lameness (Chapter 2), yet substantially larger than that estimated as a consequence of cardiopulmonary challenges (Chapter 3). This is expected, since the cardiopulmonary challenges analysed (pulmonary hypertension/ascites and SDS) are estimated to affect a much lower proportion of individuals than those affected by heat stress, and in some cases (SDS) their effects are very short lasting. Interestingly, the estimated time in Disabling pain associated with heat stress is only slightly lower than that estimated in the case of lameness. This is because the likelihood that lame individuals experience a state of Disabling pain is only high if they have severe gait scores (GS4 and GS5), which correspond to less than 5% of fast-growing birds in commercial flocks (Chapter 2).

The reduction in the hours spent in pain due to heat stress with the adoption of slower-growing breeds is clear. As expected given the higher resilience of these strains to heat and their lower metabolic rate, the time in pain spent by slower-growing birds is much lower despite their (2 weeks) longer lifetime. Overall, approximately 4 hours of Annoying pain, 25 hours of Hurtful pain and 7 hours of Disabling pain are averted for every broiler bred for slower growth.

The relatively high impact of heat stress on the welfare of conventional (fast-growing) genotypes is consistent with claims of major financial losses in the poultry industry as a result of mortality and lower weight gain due to heat stress. The findings are also consistent with observations on the role of

environmental variables on welfare indicators. For example, in a study with ten major broiler producers in the UK, most of the variation in faecal corticosteroid was explained by the effect of temperature, humidity and ventilation in the farm houses [53]. Corticosteroid concentrations were also correlated with mortality, leading the authors to suggest that stress on birds and their risk of dying greatly depended on the extent to which the house environment could be controlled [53].

Naturally, the extent to which the estimates presented here accurately represent the burden of heat stress in broilers depends on the extent to which the proportion of birds panting, as reported in the literature, is representative of the proportion of birds panting at the end of the production cycle under commercial conditions. For example, if the data reported was collected predominantly during the hottest seasons of the year, and/or from facilities where stocking densities were higher than those typical in the industry, or even in houses with poorer control of temperature and humidity, then the estimated prevalence of birds affected by heat stress (Table 2) was possibly overestimated. Conversely, if the farms visited had a better control of the environmental parameters than what is typical for the industry (a 'healthy farm' effect, whereby farms that allow visits have better welfare conditions), then the values in Table 2 possibly underestimate the effect of heat stress. Unfortunately, most research papers do not report the season and timing of data collection, nor environmental parameters to enable examining these questions. Although we used wide uncertainty ranges to incorporate the uncertainty and variability in the prevalence of animals affected by heat stress in the final estimates, further research in this area is greatly needed. Specifically, longitudinal surveys examining the proportion of birds affected by heat stress over the entire production cycle, as well as typical variations along the day and year, in top poultry producing countries, would be extremely valuable.

Still, the estimates of the impact of heat stress are likely conservative, as they do not include the indirect effects of heat stress on the health and welfare of birds. For example, behavior is greatly affected as chickens attempt to regulate their body temperature; birds will spend more time lying down and less time walking, standing and eating. The effects of heat, coupled with a reduced feed intake, also affects the birds' natural immunity, increasing the risk of infectious diseases such as salmonellosis, coccidiosis and *E. coli* infection [54]. Additionally, the reduced levels of activity also increases the risk of lameness and contact dermatitis, with significant associations between panting scores and footpad dermatitis in fast-growing strains.

V. Research Gaps and Opportunities

1. Longitudinal data on the proportion of birds affected by heat stress over the entire production cycle, as well as typical variations along the day and year, are much needed, particularly in top chicken producing countries outside Europe.
2. Data on the heat stress susceptibility of different broiler strains is currently limited.
3. To our knowledge, there have been no preference tests to date evaluating the degree of aversion that heat stress represents to broiler chickens. Further research in this area could be very valuable.

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