Monetizing the Externalities of Animal Agriculture: Insights from an Inclusive Welfare Function[*]

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Abstract

Animal agriculture encompasses global markets with large externalities from animal welfare and greenhouse gas emissions. We formally study these social costs by embedding an animal inclusive social welfare function into a climate-economy model that includes an agricultural sector. The total external costs are found to be large under the baseline parameterization. These results are driven by animal welfare costs, which themselves are due to an assumption that animal lives are worse than nonexistence. Though untestable—and perhaps controversial—we find support for this qualitative assumption and demonstrate that our results are robust to a wide range of its quantitative interpretations. Surprisingly, the environmental costs play a comparatively small role, even in sensitivity analyses that depart substantially from our baseline case. For the model to find that beef, a climate-intensive product, has a larger total externality than poultry, an animal-intensive product, we must simultaneously reduce the animal welfare externality to 1% of its baseline level and increase climate damages roughly 35-fold. Correspondingly, the model implies both that the animal agriculture sector is much larger than its optimal level and that considerations across products ought to be dominated by animal welfare, rather than climate, effects.

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1 Introduction

Raising animals for human consumption creates a host of important issues. Among the most pressing are the large effects on participants not represented in the current market: both the animals themselves and future humans, through the many greenhouse gas (GHG) emissions of this sector, have stakes in the outcome of this market. These—potentially large—unpriced externalities imply that current global production in animal agriculture may have meaningfully diverged from its efficient level.

This paper develops and applies a unified framework to jointly measure the animal welfare and climate externalities of animal agriculture. Within the disciplines of ethics and climate science, these externalities, respectively, comprise large sub-disciplines. Notably, however, there are few attempts to quantify either in a welfarist framework that allows for economic measurement, i.e., a dollar value we should be willing to pay to reduce them. Indeed, we know of no work that attempts to monetize the animal welfare externality, let alone in a unified framework that allows for straightforward addition and comparison with the better-studied climate costs. This paper performs this exercise in a fully specified economic-welfarist framework and finds these costs to be jointly substantial with the possibility of very large animal welfare costs, depending on assumptions regarding the quality of animal lives.

We begin by formalizing a population-sensitive, animal-inclusive, social welfare function (SWF). The research question concerns counterfactually unborn animals, which requires stances not only on human-animal comparisons, but also on the social value of new existences. Following numerous ethicists and economists, we work with a generalized totalist utilitarian welfare function (Blackorby et al., 1995): social welfare is the (possibly weighted) sum of utility across all beings and time. While the field of population ethics—the study of how to rank social outcomes with different population sizes—lacks consensus over this issue (Arrhenius, 2000), our choice has attractive features even for those who do not share this totalist view. First, we deduce that it produces a lower-bound on the welfare costs of animal production relative to a broad class of alternative SWFs. This is both because strict utilitarianism ignores sources of potential harms beyond the creation and discontinuation of streams of experiences in this market (Korsgaard, 2018) and because totalist population criteria will be the friendliest towards adding lives that are not terribly good. Additionally, this function permits a simple analytical representation of the marginal cost of an animal product: the sum of all (discounted utility) costs to future humans plus the lifetime utility of the animal to be used for human consumption. The former has a natural analog in the social cost of carbon; it is conceptually simple to extend these costs to a different GHG-producing activity. The latter is less understood and requires novel quantitative stances on ethical parameters.

The most consequential of these ethical parameters regards how the life of an industrially ("factory") farmed animal compares to non-existence.[1] Using an analogous welfare function, Espinosa and Treich (2021) show that it is welfare-enhancing to reduce the size of this sector *if and only if* farmed animals do not have a "life worth living." In our model, because of the additional climate externality which is always negative, this becomes a sufficient (but not strictly necessary) condition of the sector generating a negative welfare externality. Appealing to various lines of reasoning, we argue that these animals likely do not have such worthwhile lives, implying that the existence externality is negative in our baseline analysis.[2] This stance is not universally accepted (Tännsjö, 2016; Thompson, 2020), and so the baseline results are most accurately viewed as an exploration of these costs *if* farmed animals do not have lives worth living; throughout the paper, we discuss what can be learned from our model under alternative views on farmed animal lives.

This animal-inclusive welfare function is applied within an economic model, DICE-FARM, built in companion research that examines the climate costs of a range of dietary choices (Errickson et al., 2021). DICE-FARM is a modification of the Dynamic Integrated Climate-Economy (DICE) model (Nordhaus, 1992, 2017) that includes an animal agriculture sector. Formally, Errickson et al. (2021) extends DICE to capture the effects of non-CO_2 GHGs from livestock production—methane (CH_4) and nitrous oxide (N_2O)—and includes a sector that generates these emissions as a by-product of animal production. In this paper, aside from generalizing the welfare function, we further enrich that model by accounting for the number of animal life years used to produce meat within the farm sector.

Our baseline results imply that the annual social costs of an average American diet are very large: the total welfare costs to future humans and animals are monetized at values on the $100,000 order of magnitude per diet, per year. In other words, we estimate that the social loss generated from one individual's annual meat consumption is greater than $100,000. The animal welfare externality accounts for nearly all of this large sum, underscoring the degree to which the results

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[1] The physical and mental well-being of livestock vary significantly by production method and country. We assume that an industrially farmed animal is representative given the dominance of this production, not only in the United States, but in other middle- and high-income countries (Gerber, P.J., H. Steinfeld, B. Henderson, A. Mottet, C. Opio, J. Dijkman, A. Falcucci, and G. Tempio, 2013).

[2] We apply the term "existence externality" or "existence cost" in a manner distinct from the use of "existence value" in environmental economics (Krutilla, 1967). There, humans derive utility from a natural resource or living organism based on knowledge of its existence. In our setting, existence cost is taken to mean the social cost realized from livestock that experience net negative utility from living.

rely on difficult-to-test assumptions on the parameter governing the quality of farmed animals' lives. However, in robustness analyses, we demonstrate that the animal welfare externality remains the dominant consideration under nearly any quantitative representation of the qualitative claim that industrially farmed animals have lives not worth living. Under the opposing claim that these animals do in fact have net-pleasurable existences, the results are quickly reversed, though due to the lower-bound nature of the totalist utilitarian framework in this application, we are less confident about the implications of our results under an assumption of net-pleasurable lives. In either case, at both the annual diet and individual serving level, chickens are the main source of these welfare effects. Poultry has become a dominant source of protein, and the meat produced per bird is low, so each serving requires more animal lives; as a result, more than 68 billion birds are raised and slaughtered annually (FAO, 2021*b*).

There are two straightforward policy implications arising from the baseline analysis that we proceed to study. First, the large externalities associated with this market suggest that optimal policy would reduce its size. To formalize this, we add to the model private production costs and utility benefits received by consumers. Following directly from the large external costs, the welfare maximizing level of animal agriculture is much smaller than the unregulated outcome. The functional form we choose for utility implies steeply increasing marginal benefits as meat consumption declines, so the sector is not fully eliminated in our calibration, though we do not wish to stress the exact quantitative results given the many uncertainties underlying this exercise. Rather, the results suggest that any modest policy proposals to reduce the sector will be supported in our framework.

The second, and arguably more decision relevant implication, is that a substitution from beef to poultry has the possibility of being welfare reducing despite the well-known climate benefits of this substitution. A further product-level optimization problem inheriting our baseline assumptions would merely reflect that poultry has higher social costs than beef and prioritize poultry reductions. Instead, we study the robustness of the relative marginal social costs between these products to assumptions underpinning the climate and animal welfare costs. This allows us to directly study the parameter combinations that can rationalize a substitution from beef to poultry on welfarist grounds. We find only a small corner of the relevant parameter space is able to support such a substitution in this framework. For example, one such combination that equates the externalities of beef and poultry implies that our baseline analysis overestimates the animal welfare externality 100-fold *and* that DICE-FARM underestimates climate costs by roughly 35-fold; other parameters that reverse the original result are similarly extreme relative to our baseline. Given the unique uncertainties in this context, we acknowledge it is plausible that our baseline is in error by these magnitudes, though it is informative to recognize that *both* dimensions would need to be seriously modified to generate qualitatively different implications.

This paper contributes first and foremost to the sub-field of environmental economics concerned with animal welfare. A recent landmark in this literature is Norwood and Lusk (2011) which serves as a thorough treatment of the economics and ethics of farmed animal welfare. The key difference in our paper is that we incorporate farmed animals into the welfare function directly—their well-being matters for their sake—whereas Norwood and Lusk (2011) mainly ask how humans value animal welfare (see also Fleurbaey and Van der Linden (Forthcoming)). The subset of papers drawing on the inclusive concept of welfare that we apply is even smaller; Johansson-Stenman (2018) and Carlier and Treich (2020) highlight this missing literature and call for animal welfare to be directly included in economic analysis. Very few papers have attempted this. Blackorby and Donaldson (1992) and Espinosa and Treich (2021) study the properties of a joint-maximization problem over the quantity and quality of animal lives in settings where humans choose how many animals live. Within the context of climate change, Hsiung and Sunstein (2006) and Budolfson and Spears (2019) find that inclusion of wild animal welfare greatly matters for valuing climate damages, thus altering the trajectory of optimal policy. In a similar spirit, Ng (1995) and Groff and Ng (2019) study baseline wild animal welfare through an evolutionary economic framework. We build on these past conceptual works by performing, to our knowledge, the first attempt at monetizing the animal-welfare costs of a human economic activity.

To do so, we draw on and further contribute to three distinct areas of study. First, within the field of applied ethics, much has been written generally on animal welfare. Tracing its (Western) history to Bentham (1789), modern work on this topic was catalyzed by Singer (1975). Despite the well-known utilitarian frameworks of Bentham (1789) and Singer (1975), there is wide agreement from researchers across ethical frameworks that animal welfare and animal rights deserve more consideration than they receive at present (Kagan, 2019; Korsgaard, 2018). It is in response to this ethical consensus that Carlier and Treich (2020) make their call for economists to take on the challenge of evaluating animal welfare in policy decisions where it is likely to be affected.

Second, since our study concerns the number of farmed animals who ever exist, we contribute to the applied literature on social choice regarding variable population sizes. Despite the challenges of making social choices over populations of non-constant size (Arrhenius, 2000; Blackorby et al., 2005; Greaves, 2017), in any plausible conceptualization these considerations will likely be quantitatively important if included (see Lawson and Spears (2020) for an example in human settings).

We draw on the field of population ethics which has proposed a variety of rigorous frameworks for dealing with choices of this type. Although universal consensus does not exist regarding the proper social welfare function, we follow a tradition in economics that employs a generalized critical-level total utilitarian approach (e.g. Blackorby et al., 1995). This choice is in line with the small set of aforementioned papers that have formalized inter-species population ethics comparisons (Blackorby and Donaldson, 1992; Espinosa and Treich, 2021; Budolfson and Spears, 2019).

Third, as the main purpose of the paper is to sum welfare costs and compare them to widely-recognized externalities, we draw on results and models from environmental economics.[3] We direct the reader to companion research on the relationship between livestock production and climate change that develops and analyzes the integrated assessment model on which this paper relies (Errickson et al., 2021). The methods employed therein closely mirror measurement of the social cost of carbon (e.g. Nordhaus, 2017). Outside of Errickson et al. (2021), we know of only a few papers that make attempts to price the GHG externality of animal agriculture (Wirsenius et al., 2011; Springmann et al., 2016).

The paper proceeds as follows. Section 2 formalizes the welfare function and the ethical assumptions we employ throughout the paper. Section 3 presents the quantitative exercises measuring the joint and independent externalities in this sector. Section 4 discusses the policy implications of these findings and studies their robustness. Section 5 concludes.

2 Inclusive Welfare and the Social Costs of Animal Farming

In this section we present the welfare function to be used throughout the paper and provide arguments for quantifying key ethical parameters. First, we formalize the total utilitarian framework and derive the marginal welfare cost of raising animals for human consumption. We then discuss how we parameterize the ethical components introduced by this welfare function. The section concludes with a discussion of the relation between our framework and other leading alternatives.

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[3] It must be noted that, apart from substantial climate change impacts (Ripple et al., 2014), livestock farming results in sizeable land use change (Foley et al., 2005), biodiversity loss (Newbold et al., 2015), air and water pollution (Diaz and Rosenberg, 2008), drawdown of freshwater sources (Wada et al., 2010), and antimicrobial resistence (Innes et al., 2020). See Errickson et al. (2021) for a more extensive discussion of these latter impacts, which we do not consider in this work.

2.1 Interspecies Critical-Level Utilitarianism

The assumed welfare function follows that of the generalized critical-level utilitarian framework of Blackorby et al. (1995). We extend the function to include animal well-being as in Blackorby and Donaldson (1992) and Espinosa and Treich (2021). Social welfare is then defined as the sum of (socially discounted) intra-period welfare:

$$SWF = \sum_{t=t_0}^{\infty} \left(\frac{1}{1+\rho}\right)^t \Big[\overbrace{\underbrace{\sum_{i=1}^{P_t} (u_{i,t} - \underline{\text{u}})}_{\text{Human Utility}} + \theta \underbrace{\sum_{j=1}^{A_t} (u^A_{j,t} - \underline{\text{u}})}_{\text{Animal Utility}}}^{\text{Total Within Period Utility}} \Big] \tag{1}$$

Within periods the function sums human and animal populations' (P_t, A_t, respectively) welfare above some utility threshold $\underline{\text{u}}$, which we take to represent a level that is, from the agent's subjective perspective, net-neutral relative to non-existence. Note that by assuming the critical level to be a subjectively neutral existence our generalized set up becomes the special case of total utilitarianism. In what we are referring to as a neutral life, the intensity weighted duration of pleasurable experiences from the point of view of the individual equals the intensity weighted duration of displeasurable experiences; implicitly this hedonistic framing follows the tradition of Bentham (1789).

While holding fixed the concept of a neutral life across species, we acknowledge that the same external activities and stimuli produce very different internal experiences across species. An hour rolling about in mud may create a net-positive experience for pigs while creating a near-neutral (or negative) experience for humans depending on the circumstance. All of the uncertainty regarding these subjective differences across agents is subsumed in the utility terms. We note that this is not unlike the treatment of utility differences across humans in standard settings; if two humans value different experiences with different intensities, we would find it natural for those features to be part of their respective utility functions.

Likewise following from our hedonistic conception of utility, we set the welfare weight on animal utility, θ, equal to one. This choice follows a long anti-speciesist tradition (Singer, 1975). To reiterate, we recognize the tremendous uncertainty regarding how external states and stimuli translate to subjective experiences across species. One particularly relevant concern here is over the range and depth of potential utilities. It may indeed be the case that human brains generate more extreme subjective experiences, say, if contemplating a beautiful piece of art is a better human experience than the best experience a pig can have, or conversely, if losing a loved one produces more grief in humans than pigs can realistically experience. Setting θ to one only requires that *equivalent* subjective experiences are valued equally; we make no claims that other species can, in fact, have similarly good (bad) lives if things go well (poorly) for them. Unlike the constant critical levels across species, where we merely shift experiential differences into utilities rather than species-specific critical levels, the assumption of θ equal to one is ethically substantive. To see this, consider a scenario where a human and pig were in equal pain and there is a single pain killer available. If one believes it would be morally preferable to alleviate the pain of the human, this is an implicit endorsement of $\theta < 1$. Without resolving such difficult dilemmas, we note throughout the presentation of results how they depend on θ.

The additively separable structure of this welfare function implies an additional normative stance that we explicitly note before proceeding: adding a net-pleasurable life increases social welfare. Likewise, adding a net-displeasurable life reduces social welfare. These implications are first order concerns when studying a market in which humans directly control the number of animals who exist. We recognize that these implications, particularly the former, strike many as non-obvious. It is a longstanding challenge in the philosophical-economics literature to build a variable population welfare function that is consistent with a set of widely held intuitions (Arrhenius, 2000; Greaves, 2017). Totalist population criteria satisfy the most reasonable set of normative axioms in our view and the choice follows many economic studies concerned with variable population problems (Blackorby and Donaldson, 1992; Espinosa and Treich, 2021; Méjean et al., 2020). However, we note at the close of this section that this framing produces a lower-bound on the welfare costs of bringing animals into existence. Under competing conceptions of welfare, the high costs we estimate in Section 3.2 would be in fact higher. Normative disagreements on this issue need not lead to substantive disagreements with the analysis, results, and implications.

2.2 The Marginal Welfare Costs of Rearing Farmed Animals

A simple analytical expression for the social cost (or benefit) of raising an additional animal for consumption arises from this welfare function. For expositional simplicity, we temporarily assume all farmed animals have equal (annualized) utility, u^A, and introduce a new term, LS^A, to represent the lifespan of these animals. In our subsequent application we generalize the model to allow for differences in utility and lifespan across animals.

$$\frac{\partial SWF}{\partial A_0} = \left[\sum_t \Big(\frac{1}{1+\rho}\Big)^t \Big(\sum_{i=1}^{P_t} \frac{\partial u_{i,t}}{\partial A_0} \Big) \right] + \theta \times LS^A \times [u^A - \underline{\text{u}}] \tag{2}$$

The first term corresponds to the effects on humans, through time, of raising an additional animal today. We restrict these costs to the climate effects of farmed animals, ignoring local environmental and other externalities imposed by these operations. With this simplification, the human-cost term can be expanded as follows:

$$\frac{\partial u_{i,t}}{\partial A_0} = \frac{\partial u_{i,t}}{\partial T_t} \times \frac{\partial T_t}{\partial E_0} \times \frac{\partial E_0}{\partial A_0} \tag{3}$$

Welfare lost to each individual is the product of three terms: (i) utility changes for person i in year t from a warming planet, $\frac{\partial u_{i,t}}{\partial T_t}$, (ii) temperature changes in year t from an additional unit of emissions today, $\frac{\partial T_t}{\partial E_0}$, and (iii) emission changes today from an additional animal raised today, $\frac{\partial E_0}{\partial A_0}$. To simplify notation, we denote GHG emissions as a scalar, E_0. In our application, E_0 is a three-dimensional vector that includes carbon dioxide, methane, and nitrous oxide.

The animal welfare term in Equation (2) is the product of: (i) the difference in annualized utility from the critical level, $u^A - \underline{\text{u}}$, (ii) the lifespan of the animal, LS^A, and (iii) the welfare weight placed on animals, θ. The lifespan enters because the welfare function is defined per period (i.e., per year) and so u^A is implicitly defined as annualized utility.

Following simplifications in the climate-economics literature (Nordhaus, 2017), we use global averages for both humans and animals and weight average utility by the population size in each period. For humans, the utility function is assumed to exhibit constant relative risk aversion (CRRA) and to depend only on per-capita consumption, $\bar{c}_t$:

$$\sum_{i=1}^{P_t} [u(\bar{c}_t) - \underline{\text{u}}] = P_t[u(\bar{c}_t) - \underline{\text{u}}] = P_t\Big[\frac{\bar{c}_t^{1-\eta}}{1-\eta} - \underline{\text{u}}\Big] \tag{4}$$

This function is parameterized as in the DICE model and other climate-economy welfare calculations, save for $\underline{\text{u}}$ which we discuss in the following subsection. We postpone discussion of any utility garnered specifically from meat consumption to Section 4 where it becomes relevant for an optimal policy analysis.

2.3 Existence Value and Farmed Animal Welfare

The literature on the economics of animal welfare provides little guidance for calibrating the parameters that determine animal welfare costs. We begin by assuming that u^A is fixed over time. This simplification has no effect on our main results which study the marginal welfare cost of an additional animal today, as in Equation (2). We likewise assume that u^A is fixed across farmed animals. This is substantively important. Unfortunately, it is impossible to make confident statements about cross-species welfare at present. Rather than make such conjectures, we believe this uniform assumption has the benefit of rendering the analysis transparent. Where plausible cross-species differences in welfare would importantly influence the qualitative takeaways of our analysis we note this source of uncertainty. Choosing a magnitude for this now-fixed u^A—and more consequently its relation to $\underline{u}$—requires assumptions on unknowable quantities and experiences. We proceed with humility.

First, we follow studies that rely on similar calculations for humans and assume that $\underline{u}$ corresponds to lives lived somewhere near the international purchasing power parity (PPP) adjusted poverty line of \$1.90 per day (e.g. Tännsjö, 2016; Méjean et al., 2020). That is, we assume life becomes better than non-existence once consumption levels are above the current internationally-defined poverty line. On the one hand, we recognize—as do others in this literature—it may seem demeaning to suggest that millions of human beings have lives that are not worth living. We acknowledge this concern. Nevertheless, it is plausible that some human lives include more negative experiences than positive experiences. A shortcoming of our utility function is that it is only responsive to income, and so we are forced to represent the concept of a net-negative life by income levels despite the fact that many individuals below this threshold surely enjoy net-pleasurable lives. Conversely however, compelling arguments can be instead made that this \$1.90 threshold is too low. The additive nature of our welfare function leads to the well-known "Repugnant Conclusion" in which a world with an arbitrarily large population of lives just above $\underline{u}$ would be objectively better than the status quo (Parfit, 1984). If it seems implausible that a world of many individuals living on \$1.91 per day (i.e., just barely net-positive on our calibration) is better than our current world, this suggests that our assumed critical level is too conservative.

To choose a value for u^A, the utility of a farmed animal, we draw on four lines of independent reasoning that lead us to set $u^A < \underline{u}$ in our baseline. First, there are many animals, both companion animals and those raised for food, for which we find it perfectly reasonable—even "humane"—to euthanize on the animal's behalf. This implies that humans forecast net-negative experiences for these animals, else euthanasia would not be in the animal's interest. The conditions of a representative farmed animal is likely worse than living as a chronically ill or moribund house pet. By transitivity then, farmed animal lives would be below a neutral level (Matheny, 2003).

Second, in the spirit of Pearce (2021) one could perform a (very imperfect) veil-of-ignorance exercise between living one year as a human at \$1.90 per day (equivalent to $\underline{\mathrm{u}}$ by assumption) or living for one year as an industrially farmed animal. This exercise strains credulity as it requires not only imagining that one is being farmed, but having the subjective experience of an animal in these conditions. Nonetheless—if forced to choose under these tremendous uncertainties—we would expect the former to have more subjective happiness and fewer moments of stress, boredom, and pain. This implicitly suggests that we believe the utility of a farmed animal is, in expectation, lower than our assumed critical level.

Third, we can again leverage the "Repugnant Conclusion" for an informal proof by contradiction. Under our additive utilitarian welfare function, if factory farmed animals have net-pleasurable lives, some number of their existences can offset fewer (net-pleasurable) human lives. At the extreme then, a world of arbitrarily large factory farms and no human beings can be shown to generate more total well-being than our current world. To us, this seems an objectively worse state of affairs, and so it must be the case that industrially farmed animals do not contribute positively to social welfare. Equivalently, $u^A < \underline{\mathrm{u}}$.

Finally, setting aside our imperfect personal reflections on this question, survey evidence suggests the dominant view is that industrially farmed animals do not have lives worth living. In Espinosa and Treich (2021) survey participants are described the conditions that broiler chickens—the most numerous farmed animal—experience in intensive indoor rearing practices. A large majority across students, philosophers, activists, and even farmers, view these lives as not worth living.[4] Additionally, while there exist dissenting voices contending that because these animals have needs provided (such as calories and shelter from predation) their lives are worth living (e.g. Tännsjö, 2016; Thompson, 2020), our reading of the philosophical literature on animal ethics suggests that it is the dominant view that the current state of industrial farming does not result in worthwhile lives. In accordance with arguments above, many believe that even lives with these minimal needs met may be negative on the whole; a human life of solitary confinement, for example, seems to plausibly fit this description.

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[4] Participants were given a range of animal living conditions and asked to assess at which point lives became "worth living." Even for living conditions more pleasant than that of industrially farmed animals, most participants rated these as lives as not worth living.

Beyond these arguments remains quantitative difficulties that are impossible to resolve. As such, we set u^A at the arbitrary value of human-equivalent utility at \$1.00 per day, satisfying the condition that $u^A < \underline{\mathrm{u}}$. We recognize that tremendous uncertainty surrounds this monetary choice, and even the broader statement that $u^A < \underline{\mathrm{u}}$. Accordingly, we make explicit how our main results vary over a wide range of values for u^A.

2.4 Hedonistic Total Utilitarianism as a Lower Bound on Welfare Costs

The choice of hedonistic, totalist utilitarianism may strike some as inappropriate in light of several of its implications. For example, animals with vanishingly short lives—male chicks born at egg laying facilities, for example—are given no weight in our calculation. More broadly, the action of ending an otherwise worthwhile life is only represented as the lost opportunity of future utility for that being. Aside from this concern, our additive aggregation ignores other proposals within the social welfare literature to deal with the separate issues of inequality (e.g. Adler, 2008; Zuber and Asheim, 2012) and implications that arise from explicitly valuing population increases (Parfit, 1984). Resolving these differences are beyond the scope of this paper. In what follows, however, we note that our choice will capture a lower-bound on costs, and hence our ultimately large estimates serve as a starting point for tallying all possible negative welfare effects.

We first comment on the strictly hedonistic framing—that is, the only welfare loss resulting from raising an animal for food in this setting (other than the social climate costs) is the animal's instantaneous suffering summed across its life. This implies that one pig living one year is equivalent to two pigs living six months each, despite two deaths occurring in the latter case. An important dimension of morality may be omitted by this, namely that animals may have some right not to be raised merely for slaughter. In this case, we could add costs within our framework to account for the act of killing as a violation of the animal's right to be an end in the Kantian sense. Doing so would clearly increase the total social costs of animal agriculture. Indeed, Korsgaard (2018) argues from such a Kantian framework that no animal agriculture is permissible if we grant animals moral status.

Regarding aggregative methods, we can divide competing theories between those with distributional concerns and those with concerns about large populations being socially desirable merely because they are large. Theories such as prioritarianism (Adler, 2008), sufficientarianism (Shields, 2012), and rank-discounted utilitarianism (Zuber and Asheim, 2012) are proposals that give extra weight to the marginal utility of the worst off. As we assume farmed animal utilities are at or near the worst human experiences, welfare measures that prioritize the worst off are more sensitive to the plight of farmed animals than our utilitarian framework. Regarding concerns about large populations, the most widely cited alternative to totalist population criteria is instead averagist criteria which consider average welfare conditional on existence. Again, if farmed animals have lives near the bottom of the distribution of existences, an averagist welfare function will put substantial value on preventing their existence. These existences pull down average welfare more quickly than they pull down total welfare. This is most salient for lives only just not worth living—total welfare is negligibly impacted by the addition of such a life, but average welfare is pulled towards neutrality. As a consequence, frameworks that put some (or all) weight on averagist criteria will treat welfare costs as being at least as large as our totalist welfare function.

This discussion is not intended to refute competing theories nor defend total utilitarianism. Rather, it is a bounding exercise. Our results are at least as large as those that would obtain from the same economic exercise through any of the ethical frameworks discussed above.

3 Quantification of Costs in an Augmented IAM

We now describe the model used for the application—an augmented version of the DICE model—and present the results. We find that the welfare costs of global animal agriculture are very large in the case that animals do not have net-pleasurable existences: the monetized costs of producing the meat consumed for the Standard American Diet (SAD) for one person is on the order of \$100,000 per year under our baseline parameters. In other words, eliminating the production of meat required for one individual's diet for one year confers social welfare benefits equal to the benefits of increasing annual global output by more than \$100,000. This is entirely driven by the negative existence value from the sheer volume of animals produced for food—notably chickens—and therefore varies with our choice of u^A. However, for nearly any value below neutrality, the welfare costs remain large. In the case that animals have worthwhile lives, the results are quickly reversed, highlighting the importance of this parameter for appropriate policy recommendations.

3.1 Model Details: DICE-FARM with Animal Welfare

Our model builds on the DICE-FARM framework developed in Errickson et al. (2021). In that work, the focus is solely on pricing the climate externality from animal agriculture using a modified version of DICE (Nordhaus, 2017), a leading integrated assessment model. The standard

DICE model, like most macroeconomic IAMs, consist of four conceptual modules. The economic module uses current economic inputs to produce goods with a by-product of CO_2 emissions; an atmospheric module maps the history of emissions to the current stock of GHGs in the atmosphere; a climate module inputs the GHG stocks from the atmospheric module to compute temperature dynamics; and a damage module uses the temperature increases as negative inputs to the economic module. The basic trade-off is that output today increases utility directly but harms future utility indirectly through the climate-economy cycle. Section B of the online appendix contains model details.

Errickson et al. (2021) modifies DICE in two important ways to create DICE-FARM. First, an animal agricultural sector is included alongside the industrial-only output of the economic sector. This module produces meat for human consumption with the by-product of emissions from farmed animals. Emissions intensities, taken from life-cycle assessment analysis performed by the United Nations' Food and Agricultural Organization, reflect emissions from land use change, production of feedstuffs and other farming inputs, animal management, direct and indirect energy use, and post-farm activities (FAO, 2021*a*). Because farmed animals contribute a quite different mix of potent GHGs—including methane and nitrous oxide—the climate module in DICE-FARM must also be modified to endogenize the evolution and impact of these gases. For this purpose, the FAIR climate module is used (Millar et al., 2017). This modification has the additional benefit of responding to requests to substitute the climate module within DICE for one that better reflects current scientific consensus (National Academies, 2017). Additional details of these modifications and the resulting animal-environmental relationships can be found in Errickson et al. (2021).

For our welfarist exercises, we must further enrich DICE-FARM along two dimensions. First, the human-centric social welfare function in Errickson et al. (2021) is replaced by our animal-inclusive total utilitarian function. Second, we modify the farm sector to explicitly account for the number of animal-life years necessary to produce each unit of meat. For each type of meat, this is the product of (i) the number of animals slaughtered in a given year and (ii) average lifespans, which we (iii) divide by total global production. Table 1 summarizes animal life-years necessary to produce one serving size of 20 g of protein across the three animals. Chickens require the most life-years per serving due to their much smaller body mass than pigs or cows.

With the inclusion of animal welfare in DICE-FARM, the two primary externalities of this sector have been accounted for, making the social costs of animal agriculture conceptually straightforward to compute.

Table 1: Life-Years Lived per 20 g Protein

Meat Product	Life-Years
Beef	0.0017
Pork	0.0010
Chicken	0.0103

Notes: Life-years lived per serving of meat products, defined as 20 g protein (approximately one hamburger). For each product, life-years are computed as: number of animals slaughtered annually × lifespans of those animals ÷ servings produced annually.

3.2 Main Results: Animal Inclusive Social Costs of Meat Eating

The main results of the paper are the social costs of various dietary decisions, D. We define and compute these social costs in a manner analogous to the social cost of carbon (Nordhaus, 2017).

$$SC(\Delta D) = \frac{\frac{\Delta SWF}{\Delta D}}{\frac{\Delta SWF}{\Delta C}} \tag{5}$$

The numerator is the total welfare change associated with the dietary margin under consideration. We analyze both the extensive (vegetarian) margin at an annual time horizon and the intensive (per-meal) margin. The denominator is the welfare change from a marginal dollar of consumption. Conceptually, $SC(\Delta D)$ is the dollar change to which the dietary change is welfare-equivalent.

Table 2: Marginal External Welfare Costs of Dietary Decisions

	(1) Annual Non-Vegetarian	(2) 20 g Protein Beef	(3) Pork	(4) Chicken
Total	122,836.64	56.31	32.79	325.35
Environmental	47.45	0.17	0.03	0.01
Animal Welfare	122,789.19	56.14	32.76	325.34

Notes: External costs of dietary decisions in USD. Column (1) is computed by considering an extensive margin decision: whether or not to eat any meat, relative to the meat consumed in an average American diet. Columns (2)-(4) consider the intensive margin, for example the cost of eating one more hamburger. All values are computed using a discretized approximation of Equation (5).

The results of this exercise are striking under our baseline parameters[5], depicted in Table 2. The cost of an annual non-vegetarian diet relative to a vegetarian diet is estimated to be $122,837.

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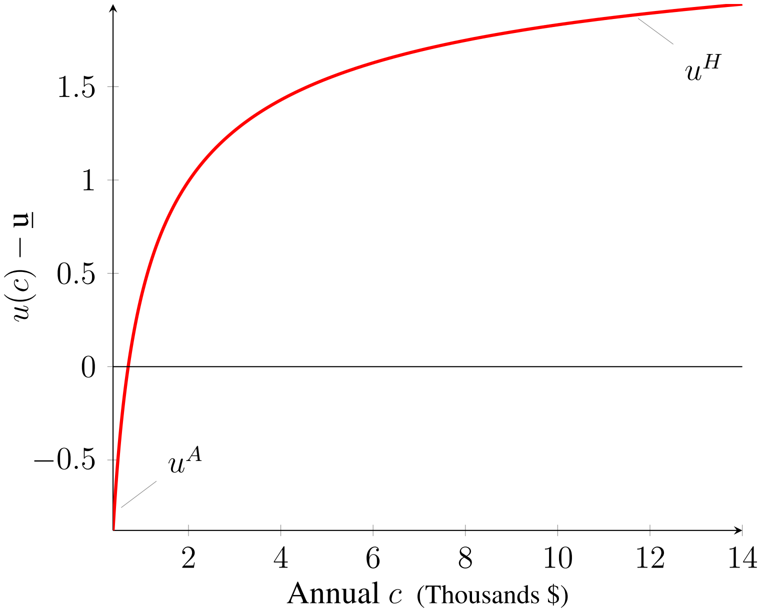
[5] As stated earlier: the parametric welfare assumptions are: u^A is equal to the utility from a human life at $1 per day, $\underline{u}$ is equal to human utility at $1.90 per day, $\rho = 0.015$, and $\eta = 1.45$. The latter two parameters are taken directly from Nordhaus (2017).

Figure 1: Concavity Implies Low Utility Levels for Animals



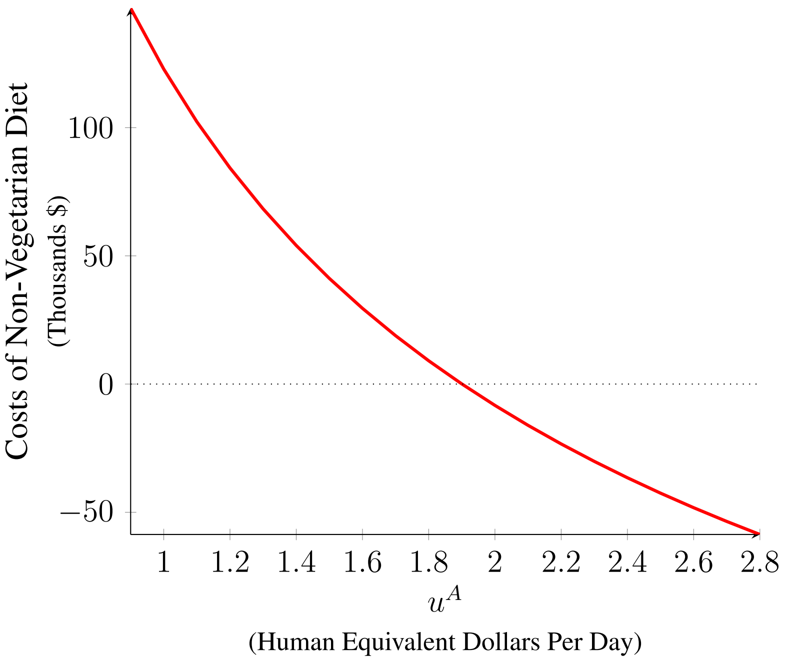
Notes: Per-capita utility as a function of income under baseline assumptions ($\eta = 1.45$). u^A is approximately -0.8 at $c = 0.365$ (thousands per year; equivalently 1 dollar per day). u^H is the utility derived at 2020 levels of global average consumption within the standard DICE model applied.

Only \$47 of this cost comes from environmental factors. To be sure, \$47 of external climate costs per person, per year, are significant when summed across the many people consuming these products, and this may even be a lower-bound given that the DICE damage function is thought to underestimate climate damages (Weitzman, 2012). However, we know of no adjustments to the climate module that can magnify these costs to the level of the baseline animal welfare costs (see Section 4.2). Bringing beings into existence with lives not worth living has significant welfare effects in this population-sensitive framework. Accordingly, the results when considered on the intensive margin (20 g of protein) are dominated by chicken despite the fact that a single serving imposes a mere penny's worth of environmental costs. The number of meals per chicken is small relative to other animals, and the value of each animal life-year is large in magnitude.

Of course, then, these large costs stem wholly from the assumption regarding farmed animals' deviation in utility from a neutral existence. The baseline results place their utility at the equivalent of a human life on \$1.00 per day. The concavity of the human utility function implies this is much worse than our assumed neutral existence in a utility-sense. To see this, Figure 1 plots $u(c) - \underline{\text{u}}$ for different values of c. Lives at \$1.00 and \$1.90 per day generate quite different levels of utility when this function is calibrated to standard values for the elasticity of marginal utility with respect to consumption.

The values in Table 2 reflect how much total global output would need to be increased to offset total social welfare losses resulting from adding some number of animal lives. Adding an animal life-year reduces total (inter-species) social welfare by about 0.8 utils. The global aggregate income gains necessary to increase human welfare by this same amount is large, approximately \$30,000, because the output gains are split among the world population. Each individual sees their consumption rise by a small quantity at a point where utility is relatively invariant to consumption. Thus, large total output gains are necessary to offset the utility losses associated with rearing an additional farmed animal (see Appendix A for a detailed derivation of this calculation).

Figure 2: Costs of Non-Vegetarian Diet by Farmed Animal Utility



Notes: Total annual costs of non-vegetarian diet, corresponding to Table 2 column (1), for different assumptions over farmed animal utility, u^A. The x-axis reports the human-equivalent-consumption that would generate the u^A used in that scenario, i.e, a value of \$1.50 here implies u^A is equivalent to the utility humans receive living at \$1.50 per day.

Despite the natural ambiguity that arises in regards to the quality of life experienced by farmed animals—and the influence that this parameter has on the results—Figure 2 shows that they remain large for nearly any choice in which animal lives are worse than neutral. This figure plots how annual social costs of an average diet varies based on different assumptions over u^A, expressed on the x-axis as human-consumption-equivalent welfare values. Our baseline paramaterization (that an animal life is the utility equivalent of living on \$1 per day as a human) corresponds to 1.0 on the

x-axis where social costs are measured near \$125,000. As animal well-being increases, the social costs of raising them for food decrease. However, even as this value approaches neutral existence (\$1.90), the costs remain well into the thousands of dollars.[6] One would have to be quite confident animal lives are nearly neutral in order for this to not be a first-order welfarist concern.

Alternatively, for the case in which farmed animal lives are worth living—values to the right of \$1.90—the costs become nearly as large and *negative*. In such a case, our framework implies very large welfare *benefits* from producing farmed animals with sufficiently pleasurable lives. While important for demonstrating that the takeaways from the baseline analysis are immediately nullified when animals are assumed to have worthwhile lives, we put little stock in the additional implications on this domain. As noted in Section 2.4 our framework likely represents a lower-bound on costs, so a demonstration of negative costs provides little actionable guidance.

Figure 2 also highlights the importance of the curvature of the utility function. Optimal climate policy greatly depends on this curvature because it governs comparisons across agents of different wealth levels (Dasgupta, 2008; LoPalo et al., 2019), as is implicit in our analysis. The online appendix shows that the large cost estimates are not driven by our assumptions over the elasticity of marginal utility (Fig. A1).

4 Policy Implications: Optimal Sector Size & Product Substitution

The baseline results in Section 3.2 point towards two distinct welfare-improving social choices. First, the large social costs of meat-eating in general suggest optimal levels of animal agriculture may be significantly lower than current levels. We formalize this conjecture by adding structure on the private consumption and production markets and performing an optimal policy exercise. Second, because the main estimates are driven by animal welfare considerations, substituting away from an animal-intensive meat (poultry) towards a climate-intensive meat (beef) appears welfare enhancing. In the case that cross-product substitution is a more active margin than uniform reductions, this is the more decision relevant finding and therefore deserves further exploration. There are significant uncertainties in both the animal welfare and climate aspects of the model that contribute to this finding; we therefore proceed by mapping the parameter space that supports the

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[6] At \$1.90, the social cost is only the environmental cost, and thus not zero. These are indistinguishable on this graph due to the required scaling of the y-axis.

original result—and conversely, the parameter combinations required to overturn it. Relative to our baseline calibration, large modifications are necessary to generate the result that beef is more socially costly than poultry.

4.1 Optimal Levels of Animal Production

Formalizing statements regarding optimal animal agriculture requires introducing utility benefits to humans from meat consumption. In a market equilibrium, private marginal benefits are equal to private marginal cost, and by documenting large external costs at current levels of consumption, we can be confident that the market outcome is higher than its efficient level.[7] As the size of this sector decreases, however, the marginal benefits of meat consumption are likely to increase. In order to estimate at what point marginal private benefits equal marginal social cost, we must impose structure on the (human) utility function.

We introduce an aggregate utility function separable in meat consumption, m. The good, m, is itself a constant elasticity of substitution (CES) aggregation of the three meat products considered in this paper: beef (B), pork (P), and chicken (C).

$$u(c,m) = \frac{c^{1-\eta}}{1-\eta} + \alpha_m \frac{m^{1-\xi}}{1-\xi} \tag{6}$$

$$m = \left(\sum_{j \in \{B,P,C\}} \omega_j q_j^{\varepsilon} \right)^{\frac{1}{\varepsilon}} \tag{7}$$

In (6), the parameter ξ measures the diminishing returns to animal products, and α_m scales the total utility from these products. In (7), the parameter ε maps to the elasticity of substitution between these goods, with higher values implying the goods are less substitutable. The ω_j parameter is a taste shifter within the CES, which allows for consumption between these goods to vary even if their prices were equal. The full parameterization, and our methods for deriving them, are detailed in the online appendix (Section C). This function is specified with features—namely, the large marginal utility of m as $m \to 0$—that conservatively anchor the resulting optimal policy to current levels of production. If large reductions are recommended under this specification, there will be little disagreement between this set up and alternative models over the desirability of more modest

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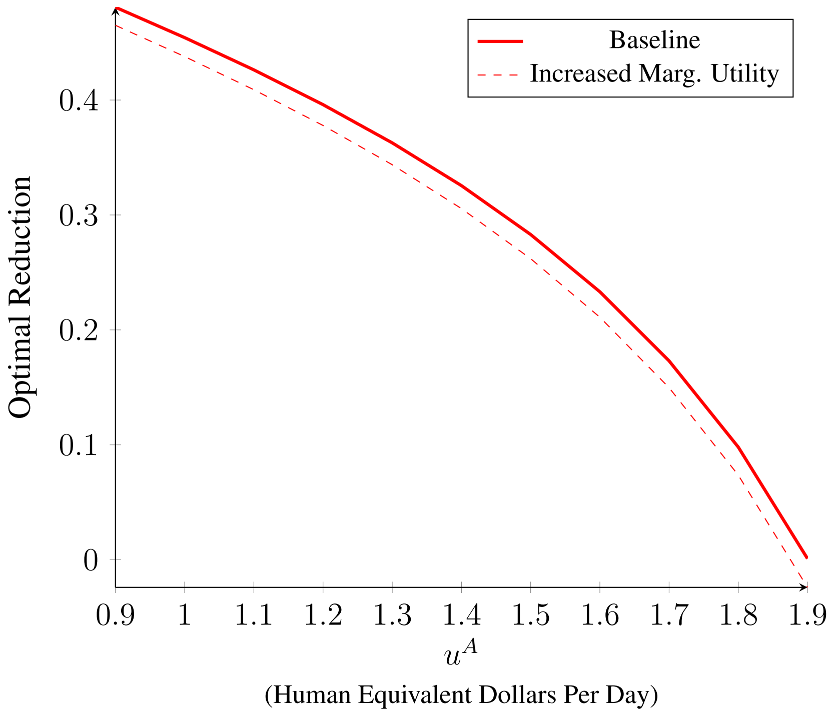
[7] Even without the existence of sizeable animal welfare externalities, global food commodity markets, including those for livestock, are distorted by a complex mix of taxes, subsidies, quotas, and tariffs (OECD, 2019). We leave for future research the study of optimal policy design in the face of these other substantial distortions and externalities.

policy proposals.

With these additions, the framework permits an optimization exercise over the size of animal agriculture. In the initial exercise, we give the planner a simple optimization over uniform reductions across all three products. The optimization problem is static over contemporaneous production. Because utility is separable across time and inputs, and the problem is dominated by animal welfare as opposed to the climate costs, there should not be meaningful differences in the fully dynamic optimization. Figure 3 presents the results along a range of animal utilities.

Figure 3: Optimal Reductions in Animal Agriculture by Animal Utilities



Notes: Optimal animal agriculture as a function of animal utility, u^a. The x-axis reports the human-equivalent-consumption that would generate the u^A used in that scenario, i.e, a value of \$1.50 here implies u^A is equivalent to the utility humans receive living at \$1.50 per day. The "Increased Marg. Utility" curve increases α_m by 10%, demonstrating that this avenue (i.e., a greater taste for meat) has small effects on the optimal policy.

Optimal reduction, if done bluntly across all animal products, is just under half (45%) in our baseline calibration: the current size of animal agriculture is nearly twice as large as it would be under this formulation of optimal policy that accounts for animal welfare and climate costs. In the functional form chosen, the marginal human-utility of meat eating increases dramatically as its production is restricted—to ∞ as $m \to 0$, in fact. Further, because global meat consumption has increased at a slower rate than incomes in the data, our calibration puts more curvature on utility from meat (m) than consumption (c). This curvature implies that the increase in marginal utility of m happens quickly, restricting the amount the planner is willing to take from humans. In light of the many layers of uncertainty underpinning this calculation—and the paucity of data on large, voluntary reductions in aggregate meat consumption—we are uncertain about the exact magnitude of optimal reductions, but feel confident that if animals have lives not worth living, such reductions would be significant.

Figure 3 takes steps towards demonstrating this by explicitly solving for optimal reductions for different levels of assumed animal welfare. For animal lives that are equivalent to human utility at \$1.40 per day or less, the reductions remain over 30%. As lives become nearly neutral (\$1.80 per day human equivalent utility), optimal reductions are still 10%—a non-trivial number given the currently large size of the animal agriculture sector and its projected growth. Interestingly, when animal lives are neutral, so that the only externality is the environmental impact, optimal reductions are indistinguishable from zero on this plot. Coupled with our conservative modeling choices, this blunt "vegetarian" tool forces reductions of pork and chicken along with beef, making it a poorly targeted climate policy option. In conjunction with Figure 2, if this axis were extended into the range where animals instead have lives worth living, the planner would recommend large increases in this sector at the expense of a warming planet. For previously stated reasons we are less confident in the reliability of our model in that region of the parameter space, so we note this qualitative difference without an accompanying quantitative exercise.

In addition to robustness along the animal welfare dimension, these optimal reductions remain largely unchanged if consumers' preferences for meat become stronger. When the marginal utility of meat consumption is increased by scaling α_m up by 10% (the dashed line in Figure 3), optimal reductions are uniformly lowered by approximately two percentage points across the distribution of animal welfare.[8] This is unsurprising given the magnitude of the social costs relative to the plausible private benefits of meat consumption.

4.2 Cross-Product Results and Robustness

Perhaps more decision relevant than the large social costs at the dietary level are the differences in these costs *across* products. These products appear relatively substitutable to consumers (e.g. Schlenker and Villas-Boas, 2009), and the large differences in baseline social costs suggest possi-

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[8] Note that under the increased marginal utility setting, animal agriculture optimally *increases* when animal lives are neutral. This is because we leave prices unchanged, so the market is temporarily out of (private sector) equilibrium at current production levels.

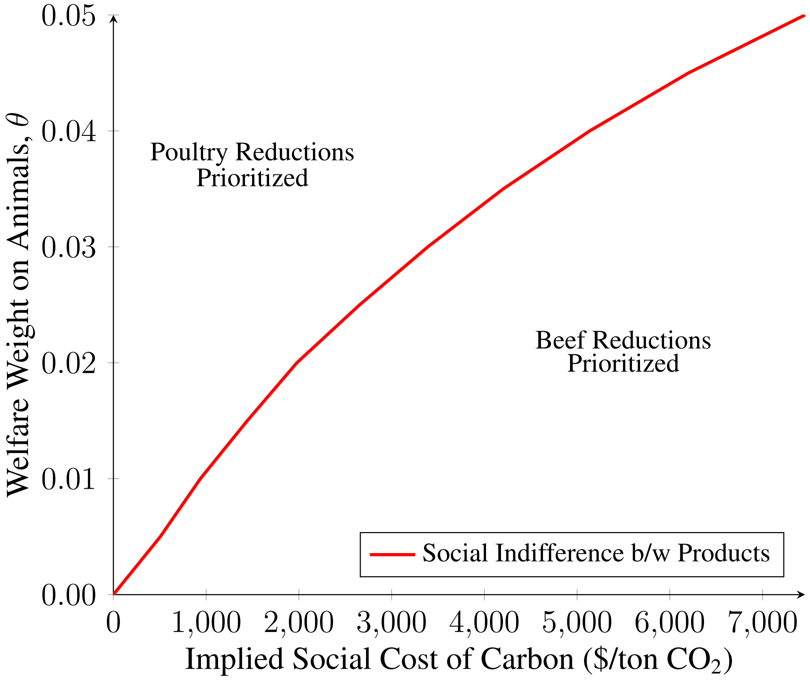
ble welfare enhancing directions of such substitution (namely, from poultry to beef). In the framework of Section 4.1, a product-specific optimization would reflect this: if poultry imposes more social costs than beef, the planner will prioritize reductions in the poultry sector (see Appendix A, Table A1). However, this qualitative result directly relies on cross-product marginal social cost differences, which themselves rely on modeling assumptions regarding animal welfare and climate costs. More informative, then, than formalizing the planner's predictable cross-product prioritization under our baseline assumptions, is to study the model modifications that retain or reject the finding that poultry has the highest social costs.

The approach we take is to map the parameter space into regions where poultry remains more socially costly than beef and regions where the opposite is true. In other words, we document what must be true within our framework to rationalize the prioritization of beef reductions. The focus is on these products because they represent the highest welfare substitution in the baseline and saliently highlight the tension between animal welfare and climate considerations. Generating a reversal of the baseline results—that beef is more socially costly—requires decreasing the size of the animal welfare externality and/or increasing the climate costs of GHG emissions. We proceed by simultaneously adjusting along both dimensions.

The results of this exercise are summarized in Figure 4. The size of the animal welfare externality, relative to baseline, is plotted on the y-axis. Recall that θ is the welfare weight on animals, which we set at 1.0 in the baseline. Because this parameter enters Equation (2) multiplicatively, reducing its value to 0.01 is analogous to scaling the animal welfare externality to 1% of its original level. Whether that arises in practice from a difference in this welfare weight or the fact that animal lives may be much closer to neutrality than we assume makes no difference here. Also note that we bound this exercise from below at 0; we continue to doubt the usefulness of the exercise generally for the case in which the baseline sign on the animal welfare externality is reversed.

The climate dimension is less straightforward. To increase the climate costs, we adjust two dimensions of the model. First, we set the social rate of time preference (ρ) to near-zero (0.001% annually). This reflects a near-equal concern for future generations and is a straightforward and ethically appealing method for increasing the value of climate damages. We then introduce a new channel whereby climate change physically impacts the rate of economic growth—in addition to the standard level effects—à la Moore and Diaz (2015). This too is a straightforward method for increasing climate damages because growth effects compound into the future (now valued at near-present levels with the discount adjustment). The social indifference curve between beef and poultry is found by solving for combinations of animal welfare weights and growth rate damages

Figure 4: Product Reduction Priorities by Welfare Weight and Social Cost of Carbon



Notes: Mapping between optimal product reductions (chicken and beef), the welfare weight on animal utility, and the social cost of carbon (SCC). Areas above the social indifference curve indicate (SCC, θ) combinations such that reducing the global poultry sector is prioritized and conversely for beef below the curve.

that equalize the marginal social costs of these products; the regions are then separated by whether they lie above or below this indifference curve. The resulting climate model—with the new discount rate and additional economic damages—is summarized on the x-axis by performing one additional step of computing the implied social cost of carbon (per ton of $C0_2$) of this parameter combination. For example, a value of 1,000 corresponds to an underlying climate module with an SCC of \$1,000 per ton of CO_2.

Figure 4 indicates that the parameter combinations necessary to prioritize beef reductions are extreme relative to the baseline calibration. Even assuming the true animal welfare costs are only 1% of our baseline value, the climate modifications necessary for indifference between beef and poultry imply an SCC of around \$1,000 per ton of CO_2. Oft-cited DICE and EPA estimates of the SCC are in the \$30-60 per-ton range (Nordhaus, 2017); common arguments for certain damage specifications and discount factors normally increase these estimates into the \$200-\$500 range. We do not endorse a particular SCC. If ethicists are correct that the social rate of time preference ought to be near-zero, a \$1,000 per-ton SCC may indeed be possible if damage functions are on the higher end of existing estimates. However, for the social cost of beef to be comparable to that of poultry, it must *also* be the case that we have overestimated animal welfare costs by two orders of magnitude. If we have only overestimated the animal welfare costs by 20-fold ($\theta = 0.05$), the SCC would need to be near \$7,000. Given this value is so large relative to any estimate we have seen in the environmental economics literature, we do not attempt to solve this indifference curve for values of $\theta > 0.05$. Despite the restricted domain of this plot, one can see that extending the vertical axis to our baseline value of $\theta = 1$ would illustrate the (very) small parameter space over which beef reductions would be prioritized.

There remain uncertainties not explored in this exercise that can overturn this result. One important source is relative welfare across animals, which remains especially uncertain. If beef cattle had much worse subjective experiences (per unit of time) than chickens, this would be an important consideration pushing against the result that poultry reductions should be prioritized. However, insofar as the literature has addressed animal welfare (e.g. Garnett et al., 2013), most believe beef cattle have better lives than industrial chickens, so we are not especially troubled by this lingering uncertainty. We do not doubt there may be concerns outside of this, but Figure 4 demonstrates that along the most important dimensions of our model, major modifications are necessary to reverse the cross-product implications of Table 2.

5 Summary & Conclusions

Despite recurring discussions and policy debate about farmed animal welfare and GHG emissions from livestock production, there are notably few economic assessments of these costs. We fill this gap by providing a rigorous study of these externalities in a unified setting and find their sum to be very large, driven by animal welfare considerations. Consequently, the current size of animal agriculture, especially the poultry sector, is much larger than it would be under the choice of a benevolent planner with an inclusive welfare function. While these costs rely on an important, untestable, assumption—that a farmed animal's life is subjectively worse than non-existence—the qualitative result is robust to a wide range of variability in how this assumption is implemented. It is not until farmed animal lives become net-pleasurable that our framework finds that this activity is not a substantial burden on social welfare.

An important limitation to this study, related to the concern about whether the representative animal has a life worth living, regards the differences in welfare across animals, even within species. To the extent that our framework estimates the social costs of a life not worth living, the results are not externally valid for conditions wherein animals do have worthwhile lives. Just because *some* animals have net-negative lives, if even that is true, does not mean our framework recommends reducing the size of operations producing net-pleasurable lives. In terms of practical policy making, the results then only apply to specific industries or firms producing animals with net-displeasurable lives. Design of such policy is beyond the scope of this paper, though we note that a majority of animals raised for food in the developed world reside in industrial farms, and these are the operations many believe do not produce worthwhile lives. This serves as a natural place to turn.

Our results echo the calls made by Johansson-Stenman (2018) and Carlier and Treich (2020) of furthering academic research in this area. While we have not resolved challenging questions at the intersection of ethics and the biological sciences regarding the subjective value of animal lives, we have uncovered what we view as important conditional results: using standard economic techniques, if animal lives are not worth living, there are tremendous social costs generated in this market. The tools of economics do not require precise values on all parameters to produce useful insights.

Accordingly, some specific future research topics that we believe economists could shed light on, if only imprecisely, are optimal investments designed to improve animal rearing conditions (from the point of view of the animal) and optimal consumption under more humane production methods. Moreover, outside of economics, the advancing work on differences in welfare across species (e.g. Schukraft, 2020) and production methods should eventually allow researchers to produce more specific policy recommendations. At the very least, our current results highlight the potential first-order nature of animal welfare questions relative to other issues competing for the attention of the welfare economics community.

Declarations

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Conflict of Interest: The authors declare no competing interests.

Data Availability: All data is available at `https://github.com/kevinkuruc/DICEFARM`.

Code Availability: All code and replication files are available at `https://github.com/kevinkuruc/DICEFARM`.

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Supplementary Appendix

A. Supplementary Results

Details of $30,000 per Animal Life Year Calculation

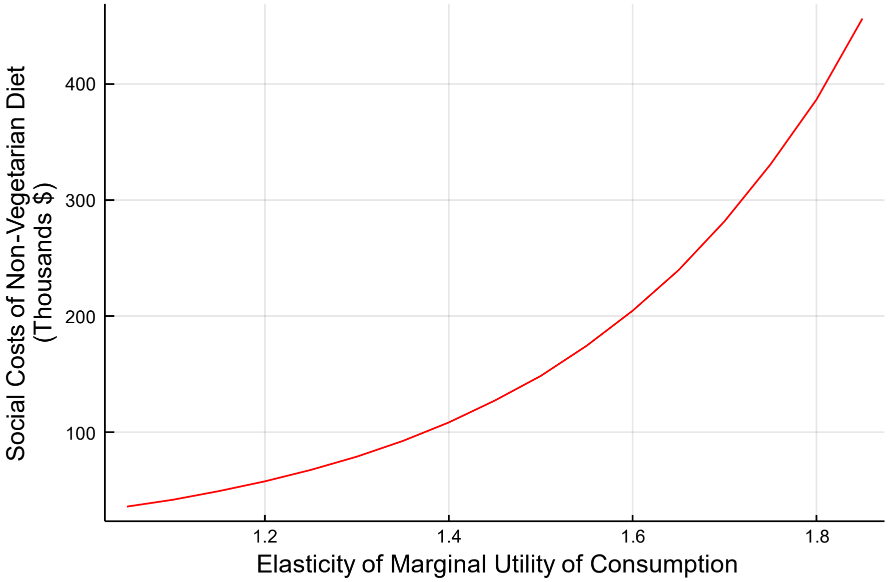
Because this number is so striking relative to the social costs of other externalities, we detail how this number is derived. Briefly, it is because the extensive margin (adding a life year) adds or subtracts much more welfare than the intensive margin of a global dollar split in the population.

To see this, notice that the marginal utility of consumption in the model is $u'(c) = c^{-1.45}$, (where c is measured in thousands of dollars). This implies that if per capita consumption increases by $1000, total global utility increases by roughly $7.8 \times 10^9 \times 11.8^{-1.45} \approx 2.2 \times 10^8$ (population size times per person welfare gain evaluated at the average per-person income of $11.8 thousand); or 2.2×10^5 per dollar.

If $1 per person (or 7.8 billion dollars total) increases total well-being by 2.2×10^5 utils and bringing an animal into existence decreases social welfare by about 0.7 utils, then we must give every person *much* less than $1 to compensate. Notice that 7.8 billion dollars generates $\frac{2.2\times10^5}{0.7} \approx 300{,}000$ times more welfare than is necessary to compensate for the animal life year. Scaling 7.8 billion down by 300,000 yields a near $30,000 result, i.e., $\frac{7.8\times10^9}{3.0\times10^5} = 26{,}000$.

Robustness to Elasticity of Marginal Utility of Consumption

Figure A1: Robustness of Main Results to η



Notes: Total social cost of a non-vegetarian (corresponding to Table 2: Row 1, Column 1) for different values of η. Our baseline value is 1.45; we experiment with values from 1 (log-utility) to 2.

An additional key model result is robustness to our choice of the elasticity of marginal utility parameter (η). This term is known to matter greatly for climate policy because comparisons of welfare across individuals—and here animals—at very different points along the utility spectrum are necessary. Figure A1 plots the robustness of our results to alternative assumptions over this parameter.

The DICE model is assumed to be on the low end of plausible values (Dasgputa, 2008), and increasing η increases the importance of minimizing animal suffering. Therefore, we feel confident our results are not driven by an unusual choice of this important parameter, and our baseline results would in fact increase for a value closer to the median of commonly used values.

Optimization by Product

Table A1, column 1 contains the main results under the baseline specification discussed in the text. When given the choice of which foods to reduce (column 2), the planner substantially reduces the chicken and pork sectors but increases beef production to make up for these losses. Chicken reduction is largest due to its high social cost per serving (Table 2). It is not entirely eliminated because of the consumer's love of variety inherent in her CES preferences; as stated, the calibration choices are intentionally favorable to leaving the sectors unaffected to generate conservative estimates. Pork is reduced and beef is increased because, while the social costs per serving of the two are similar, the data suggest that beef is the preferred product (i.e., $\omega_B > \omega_P$).

Admittedly, this latter result relies not only on the approximate level of badness of animal lives, but the relative badness between the lives of cows and pigs, for which we have much less confidence in our parameterization. Should the quality of farmed animal lives vary across sector, the industry specific reductions would respond accordingly. Additionally, unlike the meat-utility parameters from the broader utility function, the nested-CES parameters are calibrated to U.S. data only (see Section C of this Appendix). This is due to data constraints—the U.S. has the high frequency price and quantity data we need to estimate the products substitutability—and has the possibility of being misleading if globally representative data would imply different preferences across products. In a similar spirit to how we view the main analysis, here too we see this exercise as a conditional demonstration: if products are modeled to be broadly substitutable, and if the marginal external costs of products vary in they way Table 2 suggests, the planner will propose a dramatic reorganization of the sectors away from the highest cost products.

Table A1. Optimal Size of Animal Agriculture

	(1) Industry	**(2) Product Specific**
Total	0.55	--
Beef	--	1.58
Pork	--	0.33
Chicken	--	0.20

Notes: Optimal policy results, presented as the percent of the respective market's current size under: (1) blunt reduction of animal agriculture, and (2) product-specific reductions. Empty cells are objects not optimized in that specific exercise.

B. Integrated Assessment Model Details

We summarize the most relevant aspects of the unified DICE-FARM integrated assessment model (IAM) used for analysis. Much of the discussion is taken from Errickson et al. (2021); we direct the interested reader to that paper for further details.

Economic & Damage Module (DICE and Farm Sector)

We maintain the main economic relationships in the DICE model. This model has been explained in extensive detail elsewhere in the literature; see specifically Nordhaus and Sztorc (2013). We provide only a brief overview here. Gross industrial output, Y_t^G, is a function of capital, K_t, and labor, L_t; gross production has a by-product of industrial CO$_2$ emissions, $IE_t^{CO_2}$, with a linear intensity.

$$\begin{aligned} Y_t^G &= A_t F(K_t, L_t) \\ IE_t^{CO_2} &= \sigma_t^{IE} Y_t^G. \end{aligned} \tag{1}$$

The farm sector we introduce sits alongside the industrial sector and produces the three meat products in the model, beef (B), poultry (C), and pork (P). These products have a linear mapping to emission by-products of three distinct gases, carbon dioxide (CO$_2$), methane (CH$_4$), and nitrous oxide (N$_2$O). The emissions from the farm sector is therefore a nine-equation module taking the form below.

$$FE_t^{j,g} = \sigma^{j,g} j_t. \tag{2}$$

Here $FE^{j,g}$ are the farm emissions of gas g from product j; with a slight abuse of notation, j_t will represent output of product j in time t. We calibrate $\sigma^{j,g}$ to the GLEAM database (FAO, 2018). Three additional equations take the consumption of each respective animal product and (linearly) determine the number of animal life years necessary, A_t^j, to produce that product.

$$A_t^j = \Omega^j j_t. \tag{3}$$

Note that Ω^j is calibrated using 2017 data on global animal slaughters, global servings of associated meat products produced, and average lifespans of the respective animals in production. The Ω_j parameter is the number of animals slaughtered multiplied by the lifespans of those animals (total years lived by animals consumed in that year), divided by servings of the animal product in that year. We assume this is a time-invariant structural relationship. To estimate external social costs of this sector, no details on the private costs are necessary, but in the optimal policy exercises, we assume a constant marginal cost function, where the cost calibration is discussed in Appendix C.

The damage module feeds back into determining net output in the economy, Y_t^N, as in the original DICE model.

$$Y_t^N = \left(1 - D\left(T_t\right)\right) Y_t^G, \tag{4}$$

where $D(T_t)$ is a quadratic function that determines output losses due to warming in period t. DICE additionally allows for mitigation, but we omit discussion of that option here because our "Business as Usual" (BAU) model runs never take advantage of this possibility.

Atmospheric & Climate Module (FAIR)

Since the DICE climate module only endogenizes CO_2 emissions, we must import an external climate module to incorporate the major GHGs of animal agriculture. We use the FAIR model of Miller et al. (2017) as the relevant climate module. While the details of the module are more complex than those of DICE, it performs the same role conceptually: in each period, current and historical emissions of individual gases are used to predict stocks of these gases, the implied radiative forcing, and then a global temperature. The only change we make to FAIR as it currently exists is in setting the implied equilibrium climate sensitivity parameter (ECS) to the value used in the DICE model. This has the advantage of bringing our social cost of carbon calculations close to the values produced by DICE. By using a model that produces an SCC similar to that of DICE, the social cost of other economic activities is more readily interpretable in relation to other findings in the climate economics literature.

C. Calibration for Optimal Policy

Statements about optimal animal agriculture are derived from maximization of an aggregate utility function that is additively separable in per-capita consumption of meat (*m*) and all other consumer goods and services (*c*; henceforth just "consumption"). Additive separability implies that optimization can be conceptualized in two stages: 1) consumer choice of total consumption and meat to maximize within period utility, and 2) consumer choice of *individual* meat products to minimize per-period costs of total meat consumption.

This optimization requires estimates of parameters governing (sub)utility of meat consumption. We proceed in three steps. First, we lay out the consumer's first-stage optimization and characterize its solutions. Second, we detail solutions to the second-stage meat consumption choice problem and estimation of the structural meat demand parameters. Third, we discuss calibration of the remaining high-level parameters of the meat utility function.

First-Stage Lifetime Utility Maximization

The consumer's first-stage optimization problem is to choose consumption $\left(c_t\right)$, aggregate meat $\left(m_t\right)$, and savings $\left(a_t\right)$ subject to a sequence of budget constraints to maximize lifetime utility:

$$\max_{c_t, m_t, a_t} \sum_{t=0}^{\infty} \beta^t \left(\frac{c_t^{1-\eta}}{1-\eta} + \alpha_m \frac{m_t^{1-\xi}}{1-\xi} \right) \text{ s.t.} \tag{5}$$
$$c_t + P_t m_t + a_t = I_t + R_{t-1} a_{t-1},$$

where P_t is the period *t* aggregate price index on aggregate meat (note that this is a relative price with consumption being the numeraire), I_t is period *t* labor income, and R_t is the gross real interest rate. Denoting λ_t as the Lagrange multiplier on the per-period budget constraints, the first-order conditions are:

$$\begin{aligned} &[c_t] : \beta^t c_t^{-\eta} = \lambda_t \\ &[m_t] : \beta^t \alpha_m m_t^{-\xi} = P_t \lambda_t \\ &[a_t] : \lambda_t = \lambda_{t+1} \beta^{t+1} R_t . \end{aligned} \tag{6}$$

Taking ratios of the first two conditions pins down the optimality condition relating consumption of aggregate meat and other consumer goods:

$$P_t = \alpha_m m_t^{-\xi} c_t^{\eta} . \tag{7}$$

Second-Stage Optimization of Meat Expenditures

We begin by detailing the consumer's cost minimization problem over choice of meat products. Our focus is limited to beef, pork, and chicken as they are the most globally consumed meat products and, as such, are the main products for which reliable price, consumption, and production data are available (OECD-FAO, 2019). We next outline estimation of the system of demand equations resulting from the consumer's cost minimization problem.

Optimal Allocation of Expenditures by Meat Product

We assume the sub-utility function for meat consumption takes a constant elasticity of substitution (CES) specification. The consumer's problem is then to choose the three type of meat products to minimize costs:

$$\min_{q_j \in \{q_b, q_p q_c\}} \sum_{j \in \{b,p,c\}} p_j q_j \text{ s.t. } m > \underline{m},\ m = \left(\sum_{j \in \{b,p,c\}} \omega_j q_j^{\varepsilon} \right)^{\frac{1}{\varepsilon}} . \tag{8}$$

Attaching Lagrangian multiplier, ψ, differentiating with respect to q_j, re-arranging terms, and substituting in the expression for aggregate meat, m, results in the *j*th first-order condition:

$$q_j = p_j^{\left(-\frac{1}{1-\varepsilon}\right)} \psi^{\left(\frac{1}{1-\varepsilon}\right)} m \omega_j^{\left(\frac{1}{1-\varepsilon}\right)} . \tag{9}$$

Taking ratios of the *i*th and *j*th meat product for $i \neq j$ results in:

$$\frac{q_i}{q_j} = \frac{p_i^{\left(-\frac{1}{1-\varepsilon}\right)} \psi^{\left(\frac{1}{1-\varepsilon}\right)} m \omega_i^{\left(\frac{1}{1-\varepsilon}\right)}}{P_j^{\left(-\frac{1}{1-\varepsilon}\right)} \psi^{\left(\frac{1}{1-\varepsilon}\right)} m \omega_j^{\left(\frac{1}{1-\varepsilon}\right)}} = \frac{p_j^{\left(\frac{1}{1-\varepsilon}\right)} \omega_i^{\left(\frac{1}{1-\varepsilon}\right)}}{p_i^{\left(\frac{1}{1-\varepsilon}\right)} \omega_j^{\left(\frac{1}{1-\varepsilon}\right)}} = \left(\frac{p_j}{p_i}\right)^{\sigma} \left(\frac{\omega_i}{\omega_j}\right)^{\sigma}, \qquad (10)$$

where $\sigma = 1/1-\varepsilon$ is defined to be the elasticity of substitution. To derive the reduced-form expression for the aggregate price of meat, P_t, we begin with the expression for m and substitute in equation (9):

$$m = \left(\sum_{j\in\{b,p,c\}} \omega_j q_j^{\varepsilon}\right)^{\frac{1}{\varepsilon}} = \left(\sum_{j\in\{b,p,c\}} \omega_j \left(p_j^{\left(-\frac{1}{1-\varepsilon}\right)} \psi^{\left(\frac{1}{1-\varepsilon}\right)} m \omega_j^{\left(\frac{1}{1-\varepsilon}\right)}\right)^{\varepsilon}\right)^{\frac{1}{\varepsilon}}. \qquad (11)$$

Substituting in $P_t = \psi_t$ and re-arranging results in the following expression:

$$P_t = \left(\sum_{j\in\{b,p,c\}} p_j^{\frac{-\varepsilon}{1-\varepsilon}} \omega_j^{\frac{1}{1-\varepsilon}}\right)^{\frac{\varepsilon-1}{\varepsilon}}. \qquad (12)$$

Estimation of Structural Meat Demand Parameters

Log-transforming each of the three equations and appending mean-zero econometric errors results in empirical equations amenable to estimation of the structural parameters.

Estimating Equations

Based on the form of the second-stage solutions in (10), we construct the following system of three linear equations that explain relative meat consumption as a function of relative prices:

$$\begin{aligned}
\log\left(\frac{q_b}{q_c}\right) &= \sigma \log\left(\frac{p_c}{p_b}\right) + \sigma \log\left(\frac{\omega_b}{\omega_c}\right) + \mu_{bc} \\
\log\left(\frac{q_p}{q_c}\right) &= \sigma \log\left(\frac{p_c}{p_p}\right) + \sigma \log\left(\frac{\omega_p}{\omega_c}\right) + \mu_{pc} \qquad (13) \\
\log\left(\frac{q_p}{q_b}\right) &= \sigma \log\left(\frac{p_b}{p_p}\right) + \sigma \log\left(\frac{\omega_p}{\omega_b}\right) + \mu_{pb}.
\end{aligned}$$

It can be estimated from the system of equations by constraining the coefficient of the (log-transformed) relative price ratio to be equal across equations. The taste-shifting demand parameters ω_j for $j \in \{B, P, C\}$ can then be estimated from each equation's intercept.

We re-write (13) as:

$$\begin{aligned}
\log\left(\frac{q_b}{q_c}\right) &= \alpha_1 + \beta \log\left(\frac{p_c}{p_b}\right) + \mu_{bc} \\
\log\left(\frac{q_p}{q_c}\right) &= \alpha_2 + \beta \log\left(\frac{p_c}{p_p}\right) + \mu_{pc} \\
\log\left(\frac{q_p}{q_b}\right) &= \alpha_3 + \beta \log\left(\frac{p_b}{p_p}\right) + \mu_{pb}.
\end{aligned} \tag{14}$$

Note that $\omega_b / \omega_c = \exp(\alpha_1 / \beta), \omega_p / \omega_c = \exp(\alpha_2 / \beta), \omega_p / \omega_b = \exp(\alpha_3 / \beta).$ We impose the common assumption that the three taste shifters sum to one, i.e., $\sum_{i \in \{B,P,C\}} \omega_i = 1.$ Under this assumption, the taste-shifting parameters are identified as:

$$\begin{aligned}
\omega_b &= \frac{\exp(\alpha_1 / \beta)}{1 + \exp(\alpha_1 / \beta) + \exp(\alpha_2 / \beta)} \\
\omega_p &= \frac{\exp(\alpha_2 / \beta)}{1 + \exp(\alpha_1 / \beta) + \exp(\alpha_2 / \beta)} \\
\omega_c &= \frac{1}{1 + \exp(\alpha_1 / \beta) + \exp(\alpha_2 / \beta)}.
\end{aligned} \tag{15}$$

The structure of (13) implies that estimation of the third equation is unnecessary for identification.

Construction of a very short panel of U.S. weekly meat consumption and pricing data in 2018 permits estimation of the following fixed effects model. For household *i* in month *t*, we estimate:

$$\begin{aligned}
\log\left(\frac{q_b}{q_c}\right)_{it} &= \alpha_1 + \beta \log\left(\frac{p_c}{p_b}\right)_{it} + \delta_i + \nu_t + \mu_{it1} \\
\log\left(\frac{q_p}{q_c}\right)_{it} &= \alpha_2 + \beta \log\left(\frac{p_c}{p_p}\right)_{it} + \delta_i + \nu_t + \mu_{it2},
\end{aligned} \tag{16}$$

where δ_i are household fixed effects that absorb idiosyncrasies associated with specific households' meat demand, and ν_t are month fixed effects that absorb any shock common to all households purchasing meat in the same time period.

Simultaneous estimation of the constrained linear system in (16), expressed in terms of expenditures rather than quantities, is performed using maximum likelihood under the assumption that errors are jointly normally distributed.[1] To ensure estimates are representative of the U.S. population, the regressions rely on population weights provided in the main data source.

U.S. Household Meat Consumption and Regional Meat Price Data

Data on U.S. households' weekly meat expenditures are taken from the public-use microdata (PUMD) file of the 2018 Consumer Expenditure Survey (CEX). This is the most comprehensive survey of household expenditures and income conducted by the U.S. Federal government. CEX data are mainly used to revise the weights of goods and services in the "market basket" for construction of the Consumer Price Index (BLS, 2020).

We rely on data from the diary survey, which elicits information on selected household's spending, income, and demographics. In contrast to the Interview survey, which elicits information on major household purchases, the diary survey asks respondents about minor and/or frequently occurring purchases. Each participating household reports expenditures and other characteristics for two consecutive weeks before being dropped from the sample. Approximately 5,000 U.S. addresses are contacted each calendar quarter, yielding roughly 3,000 useable surveys (BLS, 2020).

Although each household provides information to the CEX diary survey for two consecutive weeks, the PUMD files do not identify dates of both weeks. However, since the month of survey is recorded, we can identify exact weeks by retaining only those households with a first survey week at the end of the month and second survey week at the beginning of the following month. This procedure results in a substantial loss of observations—roughly 85% of all CEX diary household-weeks. Unlike U.S. federal agencies interested in estimates that are representative of states, our analysis assumes that the remaining observations across the United States are adequate for purposes of analysis.[2] We therefore retain 22 survey weeks in year 2018.

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[1] Since the best publicly-available data for estimation (explained below) only contain information on expenditures, we estimate (16) in terms of expenditures. It is straightforward to transform this system into an expenditures system by multiplying the left-hand and right-hand sides by p_b / p_c (first equation) and p_p / p_c (second equation).

[2] Most U.S. households enrolled in the Supplemental Nutrition Assistance Program (formerly known as 'food stamps') tend to receive program benefits near the beginning of each month. As such, a subset of these households can experience gaps in food security at the end of the month. However, we would not expect meat demand to be different for SNAP-enrolled households than non-SNAP households. In addition, we do not expect the relationship between meat demand and meat prices to be influenced by the extent to which each households' survey times extend across month boundaries. Any such influences would likely be correlated with temporal events, which we capture through month fixed effects.

The system in (16) requires annual, per-person consumption of beef, chicken, and pork. These are expressed in kilograms of protein to permit commensurability across products. We first divide household weekly expenditures by family size. Each of these weekly observations is then rescaled to the annual time step. To convert pounds of beef, pork, and chicken to kg protein, we rely on the following conversion factors: 0.117 (beef), 0.123 (pork), and 0.123 (chicken).[3] Individual meat products and meat prices are not tracked in the CEX diary PUMD files. We therefore link the weekly household consumption data with regional, weekly meat retail prices prevailing in 2018 from the U.S. Department of Agriculture's Agricultural Marketing Service (USDA-AMS, 2020). These data are collected by USDA-AMS from publicly available data—mainly websites—of major food retailers across the United States. USDA-AMS reports weekly retail data for eight regions: Midwest, Northeast, Northwest, South Central, Southeast, Southwest, Alaska, and Hawaii.[4]

For each week and region, no single price exists for beef, pork, or chicken. Rather, prices vary significantly based on the grade (or quality of meat), cut (or location of meat on the animal), and particular item (e.g., chuck vs. round, wings vs. thighs, loin vs. ribs). We generate meat prices that accommodate and control for this variability through the use of hedonic regressions (Rosen, 1974). Underpinning these regressions is the idea that observed prices and observable characteristics of differentiated goods define a set of implicit, quality adjusted prices. For each type of meat, USDA-AMS reports a low, high, and weighted average price based on the number of reporting retailers.

For each of the eight regions, we generate quality-adjusted meat prices for beef, pork, and chicken products by first estimating separate equations of the form:

$$\begin{aligned} \overline{P}_b &= \beta_0^b + \beta_1^b GRADE + \beta_2^b CUT + \beta_3^b ITEM + \beta_4^b WEEK + \mu_b \\ \overline{P}_p &= \beta_0^p + \beta_1^p CUT + \beta_2^p ITEM + \beta_3^p WEEK + \mu_p \\ \overline{P}_c &= \beta_0^c + \beta_1^c TYPE + \beta_2^c ITEM + \beta_3^c WEEK + \mu_c . \end{aligned} \tag{17}$$

Note that $\overline{P}_i$ for $i \in \{b, p, c\}$ denotes the weighted average price for beef, pork, or chicken. The remaining non-week regressors in (17) indicate various dimensions of quality.[5] For each week

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[3] Our empirical system requires regressing the logarithms of relative meat consumption on the logarithms of relative meat prices. As many households are at corner solutions for one or more types of meat during the week, we use the inverse hyperbolic sine transformation (Burbidge, 1988). That is, we model

$$\log\left(\frac{q_i}{q_c}\right) \approx \ln\left[\left(q_i / q_c\right) + \left(\left(q_i / q_c\right)^2 + 1\right)^{1/2}\right], i \in \{b, p\}.$$

[4] For purposes of their reporting requirements, USDA-AMS defines the six multi-state regions according to the following classification. Midwest: IA, IL, IN, KY, MI, MN, ND, NE, OH, SD, WI; Northeast: CT, DE, MA, MD, ME, NW, NJ, NY, PA, RI, VT; Northwest: ID, MT, OR, WA, WY; South Central: AR, CO, KS, LA, MO, NM, OK, TX; Southeast: AL, FL, GA, MS, NC, SC, TN, VA, WV; Southwest: AZ, CA, NV, UT.

[5] In the beef regressions, GRADE indicates the grade of the meat: branded, choice, select, or other; CUT denotes the cut of beef: brisket, chuck, ground beef, loin, rib, round, or other; and ITEM indicates one of roughly 50 item types (e.g., beef patties, bone-in ribeye roast, corned beef brisket, porterhouse steak, rump roast, etc.). In the pork regressions, CUT indicates the cut of pork: ham, loin cuts, processed items, butt/picnic/spareribs, or other; and

corresponding to the 22 weeks for which we have household meat expenditures, we generate quality-adjusted prices as the average of the predicted weighted average prices from (17).[6]

Results: Hedonic Price Regressions and Meat Demand Regressions

Summary output and diagnostic results of the 24 hedonic price regressions are provided below in Table C1. Regions with the most expensive quality-adjusted meat prices in 2018 were areas with large populations located at far distances from supply centers, i.e., the Northeast ($5.87, beef and $2.97, chicken) and Alaska ($3.43, pork). Regions with the least expensive meat products tended to be those nearest major supply centers: the Midwest for pork ($2.73) and the Southeast for chicken ($2.39).[7]

Consistent with other applied studies that use hedonic methods (e.g., Berry et al., 1995), our price regressions work well. The various characteristics are jointly significant for all meat types and across all regions and explain a very large percentage of the variation in prices. For regions in the contiguous United States at least 90% of the variation in advertised pork and chicken prices can be explained by differences in cut/type, item, and the week of price posting.

Using the predicted, quality-adjusted weighted average prices from (17), our main estimates of the system in (16) are presented in Table C2. The panel regressions make use of 1,162 household observations. Estimates are used to back out the structural parameters, as in (15). The implied elasticity of substitution suggests the three meat products are imperfect substitutes.

ITEM indicates one of roughly 51 item types (e.g., backribs, spareribs, Canadian bacon, fresh tenderloin, etc.). In the chicken regressions, TYPE indicates whether the chicken product is conventional, organic, or specialty; ITEM indicates one of roughly 52 item types (e.g., breast tenders, boneless/skinless breast, drum-thigh-breast combination, leg quarters, whole rotisserie chickens, etc.).

[6] Differences in item composition do not vary substantially across the Midwest, Northeast, Northwest, South Central, Southeast, and Southwest regions owing to the large sample sizes. However, the relative frequency for some items in Alaska and Hawaii differ substantially from the mainland of the United States. As only 2.08% of our household observations are from Alaska and Hawaii, our main results are robust to dropping these households for which the hedonic prices may be relatively noisy.

[7] The relatively low price for beef in Hawaii seems to depend on the composition of advertised retail prices for this state. A larger share of the observations in Hawaii are from lower-quality and lower-priced items, such as tri-tip and chuck/shoulder/arm roast. In contrast, a larger share of the observations in the Midwest are from higher-quality and higher-priced items, e.g., boneless New York strip steak, boneless ribeye steak, T-bone steak.

Table C1. Hedonic Regression of Advertised Retail Meat Prices on Meat Characteristics

	Region							
Product	Midwest	Northeast	Northwest	S Central	Southeast	Southwest	Alaska	Hawaii
Beef								
Constant	\$5.64***	\$5.87***	\$4.62***	\$4.74***	\$5.48***	\$5.27***	\$5.17***	\$3.63***
F-stat	160.6***	160.2***	66.3***	163.2***	211.6***	85.6***	40.9***	33.95***
R^2	0.76	0.76	0.70	0.78	0.82	0.69	0.78	0.77
Adj-R^2	0.75	0.76	0.69	0.77	0.82	0.68	0.76	0.75
Obs.	5,408	5,156	3,011	4,801	4,844	3,914	1,216	1,039
Pork								
Constant	\$2.73***	\$2.94***	\$3.37***	\$2.92***	\$2.84***	\$3.07***	\$3.43***	\$3.27***
F-stat	422.1***	486.5***	215.4***	421.5***	359.7***	207.9***	79.4***	47.6***
R^2	0.95	0.96	0.93	0.95	0.95	0.92	0.90	0.86
Adj-R^2	0.94	0.95	0.92	0.95	0.94	0.91	0.89	0.84
Obs.	2,334	2,322	1,657	2,171	2,155	1,930	888	857
Chicken								
Constant	\$2.71***	\$2.97***	\$2.52***	\$2.83***	\$2.39***	\$2.53***	\$2.64***	\$2.77***
F-stat	348.9***	247.5***	144.2***	296.9***	273.6***	238.3***	52.7***	27.9***
R^2	0.94	0.91	0.90	0.94	0.92	0.92	0.90	0.83
Adj-R^2	0.93	0.90	0.89	0.93	0.92	0.92	0.88	0.80
Obs.	2,525	2,738	1,746	2,271	2,389	2,153	721	668

Notes: Significance denoted as *** p < 0.01. Not all item types are available for each meat product, and the frequency of items underlying the average predicted price varies by region.

Table C2. Meat Demand System Parameter Estimates

Variable	$\log\left(p_b q_b / p_c q_c\right)$	$\log\left(p_p q_p / p_c q_c\right)$
Constant	-0.181	2.265***
Log price ratio	-0.222	-0.222
Observations	354	354
Household FE	Y	Y
Month FE	Y	Y

Notes: Weighted maximum likelihood estimates of the expenditures system based on the constrained linear demand system in (16). Standard errors have not been adjusted to account for the generated price regressors.

Based on these estimates, we find $\beta = -1.22$, $\omega_b = 0.501$, $\omega_c = 0.432$, and $\omega_p = 0.067$.

Calibration of Meat Utility Function Parameters

There are two stages for calibration of both parameters in the consumption-meat utility function. First, we calibrate the elasticity of the marginal utility of meat consumption, ξ, using best-available international data on incomes and meat consumption. Second, we calibrate the weight on meat consumption in the per-period utility function, α_m, using best-available U.S. data on per-person meat consumption and meat prices.

Elasticity of the Marginal Utility of Meat Consumption

Taking logarithms of (7), first-differencing, and assuming that the international price, P_t, of the meat aggregator, m_t, has been roughly constant[8] over the horizons of interest results in the following equation that can be used to calibrate the elasticity of the marginal utility of meat consumption:

$$\frac{g_c}{g_m} = \frac{\xi}{\eta}. \tag{18}$$

We assume the elasticity of the marginal utility of consumption, η, is 1.45, as in Nordhuas (2017). Therefore, the parameter of interest is just proportional to the ratio of consumption growth to aggregate meat growth.

First, we generate $m = \left(\sum_{j \in \{b,p,c\}} \omega_j q_j^{\varepsilon} \right)^{\frac{1}{\varepsilon}}$ using estimates from the meat-demand regressions. Recall that our estimates of these parameters are based on U.S. panel data. However, to be consistent with the notion of a representative agent, we use best-available data on international meat consumption from the United Nations' Food and Agriculture Organization. In particular, we use global data on per-person availability of daily protein (g) from bovine meat, pig meat, and poultry for years 1961-2013 (FAOSTAT, 2020). We re-scale these data to reflect units of per-person kg protein per year.

Data on per-person annual consumption are taken from the World Bank. These data are global per-capita gross domestic product (GDP) based on purchasing power parity (PPP) in constant 2011 dollars (World Bank, 2020). Although these data are available during 1990-2018, we retain only 1990-2013 values to match those for which we have data on aggregate meat.

To allow some flexibility in time periods, we calculate growth rates according to 10 distinct rolling periods. We ultimately use an average of the rolling-window ratios as our estimate of the elasticity, indicated below in Table C3.

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[8] Recall that this is a relative price; our assumption is that the "real costs" of producing meat has not seen any large changes change between 2010-2013. In Table C3, we present results for horizons that render this assumption tenable.

Table C3 Calibration of the Elasticity of the Marginal Utility of Meat Consumptions

Window	g_m (%)	g_c (%)	ξ
2003-13	13.96	29.98	3.11
2004-13	12.74	24.99	2.84
2005-13	11.49	20.79	2.62
2006-13	9.38	16.08	2.49
2007-13	6.29	11.51	2.65
2008-13	4.70	9.75	3.01
2009-13	4.47	11.48	3.72
2010-13	2.83	7.26	3.73
2011-13	1.67	4.38	3.81
2012-13	0.88	2.21	3.66

Notes: We set $\eta = 1.45$, as in Nordhaus (2017).

For our application, we rely on the simple average of these cumulative-window averages: $\xi = 3.17$.

Weight on Meat Consumption

With this calibrated elasticity, as well as the estimates of the meat demand system, the weight on meat consumption is calibrated as:

$$\alpha_m = P_t m_t^{\xi} c_t^{-\eta} = \left(\sum_{j \in \{b,p,c\}} p_j^{\frac{-\varepsilon}{1-\varepsilon}} \omega_j^{\frac{1}{1-\varepsilon}} \right)^{\frac{\varepsilon-1}{\varepsilon}} m_t^{\xi} c_t^{-\eta}. \tag{19}$$

Given that this calibration is intended to hold for a representative agent, we rely on high-quality aggregate data for the United States. We take annual, per-person consumption of chicken, beef, and pork retail quantities from the United States for years 1975-2018. Quantity data are annual, per-capita disappearances for each meat product, expressed in pounds of retail weight (USDA-ERS, 2020a). We convert pounds of meat to kg protein using the same conversion factors as in the meat demand regressions.

U.S. national price data are annual averages of monthly per-pound prices for retail volumes of beef, pork, and a composite price for retail chicken (USDA-ERS, 2020b).[9] These prices are re-expressed in 2012 U.S. dollars using the U.S city average of the Consumer Price Index for all urban consumers. To capture per-person income, we use real gross domestic product per capita expressed in chained 2012 U.S. dollars (US BEA, 2020).

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[9] The composite chicken price is constructed by USDA-ERS as a weighted average of whole chicken prices and prices of various chicken parts. USDA-ERS chicken prices are only available starting in 1980. For the five years, 1975-1979, we proxy for the composite price by using retail prices of broiler meat from the National Chicken Council.

Inputs into the parameter calibration, at five-year increments, are presented below in Table C4. We rely on a simple average across the 44-year window, setting $\alpha_m = 0.025$ in our application.

Table C4 Calibration of the Utility Weight on Meat Consumption

Year	P_t ($/kg protein)	m_t (aggregate kg protein)	c_t (real GDP per-capita)	α_m
1975	218.44	7.98	26,134	0.062
1980	165.95	7.58	29,682	0.033
1985	143.02	7.94	33,336	0.028
1990	153.32	7.60	37,436	0.022
1995	122.54	7.99	39,875	0.019
2000	132.39	8.53	46,497	0.020
2005	131.66	8.95	50,381	0.021
2010	128.96	8.40	50,354	0.017
2015	150.75	8.57	54,213	0.018
2018	137.32	8.94	56,921	0.018

Calibrating Prices Within the Model

Because we lack global data on prices, we must take a slightly different approach to calibrating prices in our model. Our initial model period has total meat consumption by product (from FAO) and total non-invested consumption spending (from DICE). Within that first period we solve a 2-equation system that uses the FOC between meat spending and all other consumption spending as well as the fact that total meat purchases plus all other consumption must equal total non-invested consumption dollars. This pins down the aggregate price level of the meat good, and total spending on non-meat consumption (an unobserved quantity because DICE uses values for total consumption spending, which we assume to include meat). We then solve for the prices on each individual good by taking the relative consumption, our estimated taste-shifters, and the aggregate prices from the prior step for a 3-equation system.

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