Demand-Side Approaches to Improving Global Food Sustainability

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Thank you to Jon, Dave, Steve and many other mentors for advice and inspiration, and to my friends, family, and partner Julia for love and support.

Dedication

This thesis is dedicated to all people who experience malnutrition or the negative impacts of environmental change.

Research Collaborations

Chapter 1: "Food Loss and Waste in the US: The Science Behind the Supply Chain", was posted to the website of the University of Minnesota Food Policy Research Center (FPRC) on April 18, 2014.

I conducted the research with the help of my adviser, Jonathan Foley, who edited the manuscript. Paul West, Kate Brauman, Graham MacDonald, the FPRC staff and executive and steering committees, and Dana Gunders, Jean Buzby, Brian Lipinski, and Kevin Hall provided comments on an earlier version.

Chapter 2: "Love Letter to Food" was posted to YouTube.com as a video on the MinuteEarth channel on April 18, 2014.

Based on the research I conducted to create the issue brief, I led the writing of the script for the video, with writing and production input from the MinuteEarth team: Henry Reich, Emily Elert, Peter Reich, Ever Salazar, and Kate Yoshida. The video was produced collaboratively with Henry Reich and Elliot Malcolm. Nathaniel Schroeder and EpidemicSound performed the music.

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Abstract

Humanity faces the grand challenge of doubling its food supply by 2050 while reducing agriculture's already substantial impact on the environment. Supply-side approaches such as sustainable intensification may not be able to achieve this goal alone without significant efforts to reduce food waste and the consumption of animal products. This thesis presents three efforts to learn and educate about these demand-side strategies. To inform policymakers about the state of the science of food loss and waste in the United States, we created a technical issue brief. Using the principles of behavioral economics and psychology as applied to public policy, we transformed the issue brief into an accessible format, online video, to reach ~650,000 viewers. Finally, we conducted exploratory research into the potential of a global carbon tax to mitigate greenhouse gas emissions from animal protein today and in 2050, finding little evidence of its efficacy.

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Introduction

Due to population growth and rising demand for animal products, humanity faces the grand challenge of doubling its food supply by 2050 while reducing agriculture's already substantial impact on the environment (Foley et al. 2011; Tilman et al. 2011). Crop yields are not on a trajectory to double supply by 2050 (Ray et al. 2013), so sustainable intensification of agriculture has been suggested as a way to improve yields while increasing the efficiency of fertilizer, pesticide, and water use (Foley et al. 2011; Tilman et al. 2011; Mueller et al. 2012). However, supply-side efforts may not be able to achieve a decrease in overall agricultural emissions without simultaneous and significant demand reductions from reduced food loss and waste and consumption of animal products (Bajzelj et al. 2014). Therefore, efforts to reduce food loss and waste and to shift diets away from animal products should play a role in mitigating the growth in demand that is predicted to occur as both global population and per capita demand for food rise (Stehfest et al. 2009; Foley et al. 2011; Bajzelj et al. 2014; Smith et al. 2014). Reducing over-consumption is another demand-side effort that could be employed to improve both environmental and human health (Smith et al. 2014), although we do not focus on it here.

We present three efforts to improve global food sustainability through demand-side approaches. Each effort draws on a unique theory of change, is designed for a different audience, and employs distinct modes of investigation, creation, and communication tailored to that audience. Woven together by the common thread of global food system sustainability, we hope they collectively will help pull society in a more sustainable direction.

In chapter 1, we create a technical issue brief to inform policymakers about the state of the science of food loss and waste in the United States (Reich and Foley 2014), one of the leading nations in wasted food (FAO 2013). By reviewing the literature and presenting clear, concise information to policymakers whose decisions modify the structure of the society in which we all live, the hope is to guide, so that policymakers make those decisions with more, or at least some, knowledge about the issue of food loss and waste. To date, the issue brief has been distributed by extension agencies throughout the United States, viewed ~2000 times, and shared with US Secretary of Agriculture Tom Vilsack.

In chapter 2, we transform the information and message of the above issue brief into an accessible format - online video. Even the best of issue briefs is dry, dense and technical, yet people, including many decision makers, often do not make decisions through slow and thoughtful rationalizations about information. Instead, they may act on a combination of feelings, knowledge, and outside pressures. Using the principles of behavioral economics and psychology as applied to public policy (Dolan et al. 2012), we designed a video that would reach viewers' hearts as well as their minds. While "Love Letter to Food" contains nearly identical information to our issue brief, it is much more accessible and therefore has greater potential to influence behavior. For example, we crowd-sourced participants for both practical purposes and also so that viewers would be able to identify with the messengers, who would collectively imply that the norm was to feel emotional regret for wasting food – a novel and therefore salient idea that would hopefully stick with viewers and contribute to personal behavior change. To date, the YouTube video has been viewed ~650,000 times, including by Harold McGee, Michael Pollan, and the office of the US Secretary of Agriculture, and has been shared on Upworthy, Huffington Post, NY Daily News, and a number of other online media outlets.

In chapter 3, we conduct novel academic research to explore the potential of a carbon tax to reduce global demand for animal protein and mitigate greenhouse gas (GHG) emissions today and in 2050. Through our exploratory analysis we hope to create knowledge that can be leveraged by other academics to model more comprehensive methods of incentivizing sustainable food consumption. We hope that those models will be able to provide a basis to guide policymakers and further influence the decisions of people for the good of our planet.

Chapter 1

Food Loss and Waste in the US: The Science Behind the Supply Chain

Alexander H. Reich and Jonathan A. Foley

Summary of Findings

1. Roughly 40% of the United States (US) food supply (1500 calories/person/day) is never eaten, which is among the highest rates of food loss[i] globally. Addressing this loss could help reduce food insecurity and the environmental impacts of agriculture.
2. Tremendous resources are used to produce uneaten food in the US: 30% of fertilizer, 31% of cropland, 25% of total freshwater consumption, and 2% of total energy consumption.
3. Food waste generated when people discard food in homes and foodservice accounts for 60% of food loss, is mostly avoidable, and is under-emphasized as an opportunity to improve the food system.
4. Targeting efforts on reducing waste of meat has great potential to benefit both the environment and the household budget.
5. Clarifying the meaning of date labels on foods could also reduce consumer food waste.

Background

Roughly 40% of the United States (US) food supply is never eaten (Hall et al. 2009). At 1500 food calories lost per person per day, that is twice as much as most other industrialized nations (Lipinski et al. 2013) and 50% more than was lost in the 1970s (Hall et al. 2009). Producing food uses resources and causes environmental impacts, such

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[i] Definitions of food loss and waste vary. *Food loss* tends to refer to a decrease in mass or nutritional quality of food originally intended for human consumption (FAO 2011; FAO 2013), and includes *food waste,* the food fit for human consumption that is discarded or spoils in retail, foodservice, and consumption (Parfitt et al. 2010; FAO 2013).

as water pollution (Ribaudo et al. 2011), soil erosion (Montgomery 2007), and greenhouse gas emissions (EPA 2013). Discarding food drains the food supply in a world with a growing demand (Buzby et al. 2014). Despite the global importance of food loss, much remains unknown about its extent, characteristics, and causes. For instance, a landmark global study reports collectively for the US, Canada, Australia, and New Zealand: 17% of food loss occurs during harvest, 6% in handling and storage, 9% in processing, 7% in retail and distribution, and 61% in the consumption stage (Lipinski et al. 2013). The most comprehensive US study reports only retail and consumption losses (Table 1) and treats restaurants and households as the same entity (Buzby et al. 2014). Food loss in the distribution, retail and consumption stages is called food waste[i] and presents a major opportunity to improve the efficiency of the food system.

Table 1. Annual rates and values (per capita) of combined retail and consumer food loss (Buzby et al. 2014)

Added sweeteners	41%	$21
Added fats and oils	38%	$43
Dairy	31%	$87
Grains	31%	$36
Vegetables	30%	$97
Fruit	29%	$64
Eggs	28%	$10
Meat, poultry, and fish	26%	$157
Tree nuts and peanuts	15%	$7

Producing uneaten food requires a major investment of resources: 30% of fertilizer use, 31% of cropland (Kummu et al. 2012), 25% of total freshwater consumption (Hall et al. 2009), and 2% of total energy consumption (Cuéllar and Webber 2010). This food loss is the largest component of municipal solid waste incinerated or sent to landfills (EPA 2011), where it creates methane (EPA 2013). Meat has among the lowest rates of loss (Table 1) (FAO 2011; Buzby et al. 2014), but on a per pound basis, meat loss squanders the most calories (Cassidy et al. 2013) and causes the greatest environmental impact (FAO 2013), as feed and other resources used over the lifetime of the animals increase the magnitude of the loss. Loss of meat also has the highest monetary value (Table 1) (Buzby et al. 2014).

Reducing food loss would likely reduce food prices (Buzby et al. 2014), and presents opportunities to directly alleviate food insecurity through redistribution. If 30% of US food loss were redistributed, it could provide the total diet for nearly 50 million people (Gunders 2012), the number of Americans living in food insecure households (Coleman-Jensen et al. 2011). However, even though a majority of food loss is avoidable (Kummu et al. 2012), current distribution streams and income factors mean only some food could be recovered and reach food insecure populations.

Causes of Food Loss and Waste

Food loss occurs because food is perishable; it passes through complex supply chains between harvest and consumption; and it represents a small portion of total expenditures for many Americans (Buzby et al. 2014). Thus, the convenience of wasting food often outweighs the cost.

Food loss and waste have many causes, including:

- Overplanting of crops to guarantee supply (Buzby et al. 2014)
- Edible crops left in the field due to diminishing returns on investments in harvesting (Buzby et al. 2014)
- Damage, contamination, or inefficiencies in harvest, storage, processing, and distribution (Buzby et al. 2014)
- High cosmetic standards leading to culling of visually imperfect products (Gunders 2012; Buzby et al. 2014)
- Overstocked product displays at stores (Gunders 2012)
- Inconsistent date labels that confuse consumers, leading to premature disposal (Parfitt et al. 2010; WRAP 2011; Gunders 2012; Broad Leib et al. 2013)

- Over-preparation, large portion sizes, and aversion to eating leftovers (Gunders 2012)
- Lack of awareness about the occurrence and impacts of food waste (Gunders 2012)

Initiatives to Reduce Food Loss and Waste

In June 2013 the United States Department of Agriculture (USDA) and Environmental Protection Agency (EPA) launched the US Food Waste Challenge, a joint effort of producer groups, processors, distributors, retailers, food service, and government with the goal of leading "a fundamental shift in how we think about and manage food and food waste in this country" (USDA 2013). The EPA also runs a Food Recovery Challenge to help businesses and organizations measure and reduce their food loss. Organizations working to reduce food waste include the food industry's Food Waste Reduction Alliance, hunger alleviation groups, and environmental non-governmental organizations (NGOs) like World Resources Institute, which is leading an effort to develop a global standard for measuring food loss and waste. This work should be complemented with further US-focused research, as much remains unknown about US food loss, especially regarding the relative importance of the causes of food waste.

Recommended Actions

- Standardize and clarify date labels on foods to help reduce consumer food waste. (Broad Leib et al. 2013)
- Target efforts on reducing waste of meat, which would benefit the environment (FAO 2013) and household budgets (Buzby et al. 2014).
- Institute a national research program to identify the quantity and causes of food loss and waste as a step towards committing to reduction targets (Lipinski et al. 2013; Buzby et al. 2014).
- Create public awareness campaigns devoted to reducing consumer food waste. A United Kingdom campaign helped reduce household food waste by 19% from 2007 to 2012 (WRAP 2013).

Chapter 2

Love Letter to Food

Alexander H. Reich, the MinuteEarth Team, and Elliot Malcolm

Figure 1. YouTube video thumbnail

YouTube Video URL

https://www.youtube.com/watch?v=-5i-dCv7O8o

Video File

Submitted to GSSP with thesis

Video Transcript

“Dear Food,

You probably already know this, but I need you.

You bring my family together, you sweeten my celebrations, you make my deals, you satisfy my senses, and you just plain keep me alive.

You work so hard to make all of this possible, spending your life growing in the field, the factory (farm), or the sea. I try to be good to you, giving you half of my land, two thirds of the freshwater I consume, a tenth of my energy, and one-sixth of my workforce.

But I want to apologize.

Because after all that, you deserve to be eaten. But instead, I throw almost half of you away - enough calories to feed 150 million people. From harvest to home, I waste half of all fruits, vegetables and seafood, and a third of all grains. I’m better to meat and dairy, wasting only 20 percent, but this is a double waste, because essentially I’m also dumping the grain or grass the animals ate to make the muscle or milk.

And I waste you in many ways:

Sometimes I leave you in the field to die because it costs more to harvest you than you’re worth. Other times, I mistakenly damage, contaminate, or spill you. Or, I reject you when you’re imperfect because I judge by appearance.

But mostly I squander you in supermarkets, restaurants and homes, when you are so close to being eaten.

I offer too much of you, so I take too much and I can’t finish you, or I can’t sell all of you. At home I forget about you or I cook too much and don't know how to store you. Or maybe I just don't like leftovers.

Part of the problem is that on average, I spend a smaller fraction of my household budget on you than in any other country or any time in history, and my spending is spread out over days and weeks so I don't notice the cost of wasting you.

But my lack of noticing adds up: I devote four California's worth of land and more water than all non-agricultural water consumption combined - just to grow food that doesn't get eaten.

This is not your fault - it's mine. Only I can buy less of you and eat more of what I do buy. Only I can accept your imperfections, realize that "best-before" doesn't mean "use-by," store you better, and in general, learn more about you - because this is about us and our relationship.

I help you grow, and then I eat you. Anything else is a waste."

Video Sources

The video utilized the same sources as the issue brief, as well as the following:

EPRI. 2013. Evaluating Thermoelectric, Agricultural, and Municipal Water Consumption in a National Water Resources Framework. Palo Alto, CA. 3002001154. Electric Power Research Institute (EPRI).

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USDA-ERS. 2013. Food expenditure patterns among selected countries. http://www.ers.usda.gov/media/434516/foodexppatterns.xls

USDA-ERS. 2013. Table 7—Food expenditures by families and individuals as a share of disposable personal income. http://www.ers.usda.gov/data-products/food-expenditures.aspx#.U1B0F-ZdXdV

Chapter 3

Taxes Are Not Enough:

Climate Consequences of the Shift Towards Meat

Alex Reich and David Tilman

Introduction

At a global level, income correlates with diets high in calories (Tilman et al. 2011) and meat (Bonhommeau et al. 2013; Tilman and Clark 2014). As income levels rise in developing countries, it has been projected that their people will consume diets with greater total calorie requirements, mostly driven by demand for animal products (Delgado 2003), which require more land (Kastner et al. 2012; Cassidy et al. 2013) and water (Jalava et al. 2014) and emit more greenhouse gases (Steinfeld et al. 2006; Tilman and Clark 2014) than if humans directly consumed plants as food. This demand trajectory combined with projected population growth (World Bank 2015) indicates that by 2050 agriculture and related land use change alone will produce almost the full allowance of annual greenhouse gas emissions the entire world can emit while avoiding 2 degree C temperature increase (Bajzelj et al. 2014).

Efforts to shift diets away from, or to slow a shift towards, animal-based foods can play a role in mitigating these and other negative impacts of agriculture on the environment and on human health (Foley et al. 2011; Tilman and Clark 2014). In fact, a decrease in overall agricultural GHG emissions may not be possible without significant demand reductions (Bajzelj et al. 2014). Including the livestock sector in comprehensive climate mitigation policies (Ripple et al. 2014) and implementing a carbon tax have been suggested as promising mechanisms (Nordgren 2012; Ripple et al. 2014). We explore the potential of a livestock consumption emissions tax (“carbon tax”), which has been modeled for individual countries (Edjabou and Smed 2013; Sall and Gren 2015), the European Union

(Wirsenius et al. 2011), and at a global level for methane (Key and Tallard 2012). To our knowledge, no study has modeled such a carbon tax at a global level or to 2050.

First, we identify a number of factors that could plausibly play a role in addition to income in determining the demand for animal protein globally. We evaluate these factors as predictors of demand, concluding that income and urbanization are the most available and effective predictors. We then use income and urbanization along with commodity-specific prices to model the own- and cross-price elasticity effects of a carbon tax to reduce greenhouse gas emissions from the production of animal proteins today and in 2050. Our within-country model suggests that price increases would be ineffectual, while our across-country model indicates a more sanguine outcome: an ~18% reduction in total GHG emissions today with a carbon tax at the value of the social cost of carbon (SCC). In all scenarios, however, total emissions from animal production in 2050 would be at least 90% greater than today, due to rising incomes, urbanization, and growth in total population. Our research, while preliminary, suggests that a carbon tax alone will be insufficient at mitigating emissions from the production of animal protein; technical, educational, ethical, cultural, and policy approaches will likely all be required.

Methods

Total population and urbanization (and forecasts)

We used total and urban population data from the World Bank for 1961-2009 as well as forecasts for 2050 (World Bank 2015), from which we calculated the percent of population living in an urban setting for 1961-2009 and forecast urbanization percent for 2050.

Per capita GDP (and forecasts)

We use gross domestic product (GDP) data for 1961-2009 from the Total Economy Database of the Groningen Growth and Development Centre, New York, expressed in real 1990 international dollars (1990 $) (2013). We divided this by total population from the World Bank (2015) to calculate per capita GDP. We forecast 2050 real per capita GDP using the equation developed by Tilman et al. (2011) to determine per capita real GDP growth rates from real per capita GDP. We forecast per capita GDP for each nation independently with the exception of the nations in Group F of Tilman and Clark (2014) (Table 2), which we fit collectively, given greater uncertainty about income projections for nations of such low per capita income levels.

Animal Proteins

We use annual national level data from the United Nations Food and Agriculture Organization (FAO 2015) divided by total population from the World Bank (2015) to calculate per capita daily demand for poultry meat, pork meat, ruminant meat (cattle, buffalo, sheep and goats), seafood, eggs, and milk on a protein basis. Although butter is an animal product with high emissions, it was excluded because it provides no protein, our unit of measurement. We ultimately excluded seafood from our analyses because the FAO does not provide national producer prices for seafood (see below). We use the term "demand" rather than "consumption" as we do not account for household food waste, which has been estimated as up to 11% for meat, 33% for seafood and 15% for milk by weight in wealthy regions (FAO 2011).

Prices

We calculated the national average prices received by producers for our animal proteins from annual national average prices aggregated for commodities from the FAO (2015). To make the prices consistent with the units of per capita GDP, we converted them to 1990 $ with a purchasing power parity conversion factor from the World Bank (2015) and a personal consumption expenditure price index from The Economic Report of the President (2015). Previous studies (Fiala 2008) have also used these producer prices as proxies for local consumer prices. Only 54 of our initial 100 countries reported prices for all animal types (Table 2). These 54 countries represent 52.6% (53.1%) of the world average 1991-2009 (2050) population.

Table 2. Countries with price data

Economic Group of Tilman and Clark (2014)	Analyzed Countries
A	Australia, Austria, Canada, Denmark, Finland, France, Ireland, Japan, Netherlands, Norway, Sweden, Switzerland, United Kingdom, United States
B	Chile, Greece, Israel, Italy, Malaysia, Mauritius, New Zealand, Portugal, South Korea, Spain, Trinidad and Tobago, Uruguay, Venezuela
C	Brazil, Colombia, Ecuador, Mexico, South Africa, Thailand
China	China
D	Bolivia, Dominican Republic, Egypt, El Salvador, Indonesia, Lebanon, Paraguay, Peru, Philippines, Sri Lanka
E	Cameroon, Honduras, Mozambique, Nicaragua, Nigeria, Senegal
F	Guinea, Kenya, Mali, Nepal, Rwanda and Burundi

As the FAO does not provide national level producer price data for seafood, we attempted to use the FAO Fish Price Index, calculating annual regional averages from Tveteras et al. (2012). However, we could not add a carbon tax (below) to an index. Additionally, the Fish Price Index, while capturing broad trends within regions across time, was not found to be useful for cross region comparisons, as all regions are indexed at 100 for 2002-2004. The same indexing issue prevented our use of the FAO Food Price Index and Meat Price Index.

As is common in estimates of demand for meat (Okrent and Alston 2011), we assume two-stage budgeting, in which people divide their budget between foods and other goods, and then between animal proteins and other foods. While there is some empirical evidence to support these assumptions, full policy analysis should include prices for additional food and non-food categories (Moschini et al. 1994).

Carbon tax

To calculate the carbon tax to levy on the production of the animal products in our study we multiplied mean food production GHG emissions values from a survey of 120 life cycle analyses (Tilman and Clark 2014) by the mean social cost of carbon (SCC) from a survey of 232 estimates (Tol 2009), converted to 1990 $ as $133.37/tonne CO2 C equivalents (Table 3). The tax would increase the average price of a gram of protein by the social cost of the GHG emitted to produce the protein - as little as 4.3% for eggs to as much as 16% for ruminants. These percentage increases are nearly identical to the rates used in a study of the potential impact of a carbon tax in the European Union (Wirsenius et al. 2011).

Table 3. Calculation of carbon tax. Mean g CO2 eq C / g protein are from Tilman and Clark (2014), SCC is from Tol (2009). All prices are in 1990 $.

	Mean g CO2 eq C / g protein	Tax (SCC/g protein)	Average Price / g protein (1991-2009)	Average Price + Tax	Percent Increase	Average Price + 5 * Tax	Percent Increase
Poultry	10	0.0013	0.0294	0.0308	4.5	0.0361	22.7
Pork	10	0.0013	0.0303	0.0316	4.4	0.037	22
Ruminants	62	0.0083	0.0517	0.06	16	0.0931	80
Eggs	6.8	0.0009	0.0211	0.022	4.3	0.0256	21.5
Milk	9.1	0.0012	0.0172	0.0184	7.1	0.0233	35.3

Results

Predictors

We began by investigating a number of variables as predictors of demand for animal protein (see Appendix) over the period 1961-2009. We concluded that income as well as urbanization parsimoniously explained a remarkable proportion of the variation. As these predictors were also available for projecting, we include only per capita GDP and urbanization in our assessment of the potential impact of a carbon tax.

Models

We created two systems of demand equations to incorporate price-related substitution dynamics between different types of animal proteins. As we use the same predictors in all equations, each system is equivalent to a set of seemingly unrelated regressions (Zellner 1962), found to be the most common method for modeling the price elasticity of meat demand in a meta-analysis that also identified country as the most common level of aggregation (Gallet 2010). A fixed effects analysis models relationships through time within countries (Table 4) by including dummy variables for each country to control for unobserved variables that differ between countries (Wooldridge 2012), and an analysis with time-averaged data models relationships across countries (Table 5). We explored using a random effects model, but the results were similar to the fixed effects model and a Hausman test suggested that the errors were correlated with country. We include eggs and milk as well as meat in our analysis because emissions for eggs and milk are only slightly lower than those for meats on a per protein basis (Table 3) and demand for all types of animal protein increases with income, not just demand for meat.

Table 4. 1991-2009 within (fixed effect) model. Parentheses show Driscoll-Kraay standard errors, which are robust to serial and cross-sectional correlation (Hoechle 2007).

	Dependent variable:				
	PoultryLog	PigLog	RuminantsLog	EggsLog	MilkLog
pcGDPLog	0.801***	0.531***	0.119*	0.343***	0.419***
	(0.035)	(0.128)	(0.054)	(0.064)	(0.036)
UrbanPct	0.008	-0.002	0.003	0.003	0.001
	(0.005)	(0.006)	(0.003)	(0.006)	(0.004)
PoultryPPLog	-0.088	0.027	0.044	0.099	-0.031
	(0.056)	(0.102)	(0.026)	(0.068)	(0.034)
PigPPLog	0.054	0.098	0.234***	0.001	0.038
	(0.045)	(0.079)	(0.059)	(0.041)	(0.056)
RuminantsPPLog	0.024	0.089	-0.241***	0.005	-0.047
	(0.030)	(0.067)	(0.071)	(0.051)	(0.031)
EggsPPLog	-0.064**	-0.113*	-0.107***	-0.090***	-0.014
	(0.025)	(0.047)	(0.022)	(0.015)	(0.032)
MilkPPLog	0.008	-0.024	0.064	-0.054	0.102
	(0.039)	(0.091)	(0.047)	(0.076)	(0.059)
Observations	724	724	724	724	724
Adjusted R^2 (within)	0.376	0.157	0.106	0.100	0.185

*p<0.05; **p<0.01; ***p<0.001

The within-country analysis reveals that income has been a more important correlate of all types of land animal protein demand than urbanization or prices. The coefficients of income range from 0.119 for ruminants to 0.801 for poultry and are much greater than the majority of the price elasticities, a pattern also reported in Fiala (2008), who uses the same producer price data to forecast demand of beef, chicken and pork to 2030. Urbanization never appears as a significant predictor, although its coefficient is positive for all responses except pork. An increase in the price of eggs appears to correlate with reduced demand for all types of animal proteins, whereas an increase in the price of pork correlates with increased demand for ruminants, which experience an equivalent reduction in demand when their own price increases. That ruminants have the greatest own-price elasticity is encouraging, as ruminants are responsible for 80% of livestock emissions (Ripple et al. 2014). However, the within-country analysis provides little overall evidence of statistically or practically significant relationships between prices and demand. Additionally, these predictors only explain 10-37.6% of the variation in demand within individual countries; much is left unexplained.

These same predictors, when averaged by country, explain a much greater proportion of variation in the responses in the across model (Table 5). In this model, income is the most consistent predictor, with coefficients falling in a smaller range than in the within model, even though income is no longer a statistically significant predictor for pork and ruminants. Similarly, urbanization is a consistently positive predictor of demand, although not significantly so for pork or milk. The own- and cross-price elasticities are generally greater than in the within model, an indication that the price differences between countries are correlated with greater differences in demand than when analyzing within countries. However, only the cross-price elasticity of pork prices on poultry demand and the own-price elasticities of poultry and pork are statistically significant. The negative own-price elasticity of ruminants is significant at the $p<0.1$ level, while the positive own-price elasticities of eggs and milk are highly insignificant.

Table 5. 1991-2009 across model. Parentheses show standard errors

	Dependent variable:				
	PoultryLog	PigLog	RuminantsLog	EggsLog	MilkLog
pcGDPLog	0.422*	0.205	0.219	0.535***	0.540**
	(0.172)	(0.340)	(0.153)	(0.148)	(0.184)
UrbanPct	0.022***	0.004	0.015**	0.018***	0.008
	(0.006)	(0.011)	(0.005)	(0.005)	(0.006)
PoultryPPLog	-1.024**	-0.695	0.159	-0.039	-0.219
	(0.348)	(0.690)	(0.309)	(0.300)	(0.373)
PigPPLog	0.780*	-1.828**	0.041	-0.219	-0.286
	(0.337)	(0.667)	(0.299)	(0.290)	(0.361)
RuminantsPPLog	-0.140	0.587	-0.442	0.038	-0.429
	(0.259)	(0.513)	(0.230)	(0.223)	(0.278)
EggsPPLog	0.081	0.756	0.097	0.086	0.060
	(0.192)	(0.380)	(0.170)	(0.165)	(0.206)
MilkPPLog	0.471	-0.625	-0.290	0.442	0.509
	(0.387)	(0.766)	(0.343)	(0.333)	(0.415)
Constant	-0.093	-7.015***	-1.524	-0.015	-0.339
	(0.929)	(1.838)	(0.823)	(0.799)	(0.995)
Observations	54	54	54	54	54
Adjusted R^2	0.709	0.595	0.584	0.692	0.630

*p<0.05; **p<0.01; ***p<0.001

Projections

The within model and the across model are two different ways of representing the relationships between demand for animal protein and income, urbanization, and prices. Each can provide useful insight into the changes in demand that could result from adding the social cost of the carbon emissions from the production of each animal protein to the cost of protein from that animal, such through a carbon tax. We use both models to predict levels of demand under three scenarios, which we compare to the baseline of "current" 1991-2009 average demand with no tax. We compare to 1991-2009 average demand rather than 2009 demand because not all countries have prices for all types of animal in 2009, and our across model was generated from 1991-2009 average values. We determined that this only slightly exaggerates the comparisons to 2050; the 1991-2009 average demand for animal protein was 28.9 g while the 2009 average was 30 g, an increase consisting almost entirely of poultry. In the first scenario we add the carbon tax to the current price. In the second scenario we assume that current prices remain constant in real terms to 2050 but that urbanization increases to the levels predicted by the World Bank (2015) and per capita income increases according to the methods of Tilman et al. (2011). In the third scenario we add the carbon tax to prices in the second scenario. For each scenario we calculate per capita GHG emissions and total GHG emissions, based on current and projected 2050 populations (World Bank 2015).

If the fixed effects model is taken as a model of how countries act as prices, income and urbanization change, prices will be ineffective as a lever now or in 2050, when we project daily per capita animal demand to increase by ~13 g (45%) regardless of price scenario (Fig. 2a). Adding a carbon tax to current prices would decrease average daily demand a negligible 0.03 g (0.1%), although the composition would shift, with increases of 0.09 g (1.7%) in pork and 0.11 g (1%) in milk demand, and decreases of 0.02 g (0.3%) in poultry and 0.03 g (1.3%) in eggs, and a slightly greater decrease of 0.18 g (3.8%) in ruminants. As a result of this compositional change, current average annual per capita emissions would decrease by 3.55 kg $CO2$ C eq (1.9%) (Fig. 2b), with a total emissions decrease of 0.008 Gt (1.55%) (Fig. 2c). These changes are far within the range of uncertainty. However, we project a more substantial increase in per capita annual emissions of 57 kg (30%) by 2050, resulting in a 0.45 Gt (90%) increase in total emissions. Adding the tax to prices in 2050 would decrease annual per capita emissions 4.3 kg (1.75%) and annual total emissions 0.013 Gt (1.3%) compared to 2050 demand with constant prices. In sum, per capita demand and emissions and total emissions are likely to increase greatly towards 2050, with little evidence of mitigation from price increases at the scale of the social cost of carbon.

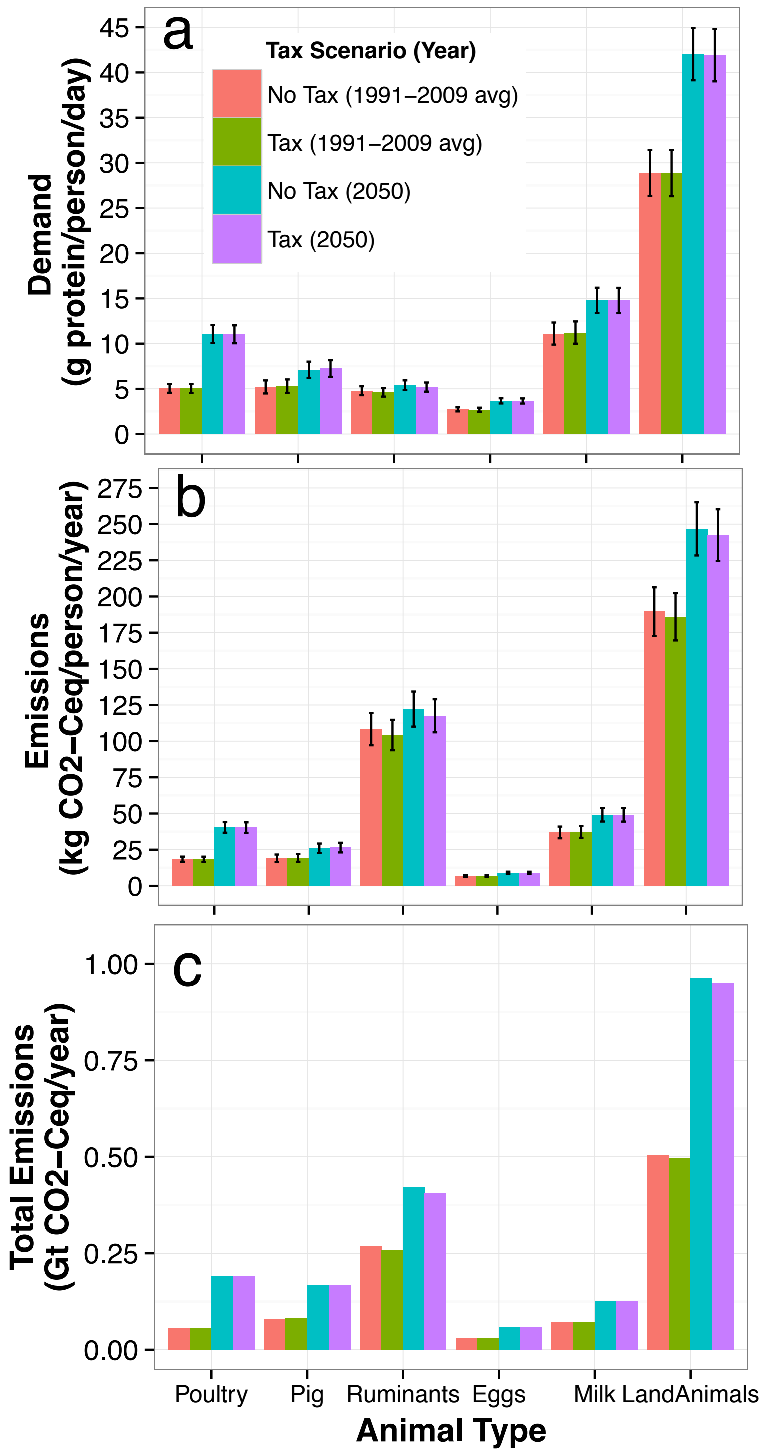

Figure 2. 1991-2009 fixed effects model current ("No Tax (1991-2009 avg)") and predicted **a.** per capita animal protein demand, **b.** per capita emissions, and **c.** total emissions. Error bars represent the standard error of the 54 countries around the mean.

If instead of modeling based on within-country relationships, we predict based on across-country relationships, we find that price may have greater potential as a lever, although its overall effect is still much smaller in magnitude than the impacts from projected income growth and urbanization. Adding the tax to current prices would decrease average daily animal protein demand by 4.18 g (14.5%), with decreases of 0.38 g (7.6%) in poultry, 1.13 g (21.76%) in pork, 0.95g (19.9%) in ruminants, and 1.73 g (15.5%) in milk, and a minimal increase of 0.02 g (0.79%) in demand for eggs (Fig. 3a). As a result of these fairly sizeable decreases in per capita daily demand, per capita annual emissions would decrease 32.76 kg CO2 C eq (17.3%), stemming from reductions of 1.4 kg (7.6%) from poultry, 4.14 kg (21.76%) from pork, 29.75 kg (21.5%) from ruminants, and 5.75 kg (15.6%) from milk, which would far outweigh an increase in emissions from eggs of 0.05 kg (0.79%) (Fig. 3b). These per capita emissions reductions would correspond to a total emissions reduction of 0.093 Gt (18.46%) (Fig. 3c).

Based on this model, we project per capita daily animal protein demand to increase 11.8 g (40.9%) by 2050 (Fig. 3a), corresponding to an increase in per capita emissions of 64 kg (33.8%) (Fig. 3b) and an increase in total emissions of 0.52 Gt (103.8%) (Fig. 3c). Adding the tax to prices in 2050 would decrease annual per capita emissions by 20.2 kg (8%), and total emissions by 0.068 Gt (6.6%). This is approximately 1/4 the magnitude of the reduction in per capita emissions and 2/3 the magnitude of the reduction in total emissions our model suggests would occur if a tax were added to prices today; growth in income and urbanization will dampen the future potential of prices as a lever. Even with the addition of a tax to prices in 2050, current per capita daily demand would grow 9.5 g (32.9%), per capita annual emissions would grow 43.8 kg (23.1%) and total emissions would grow 0.456 Gt (90.3%) by 2050.

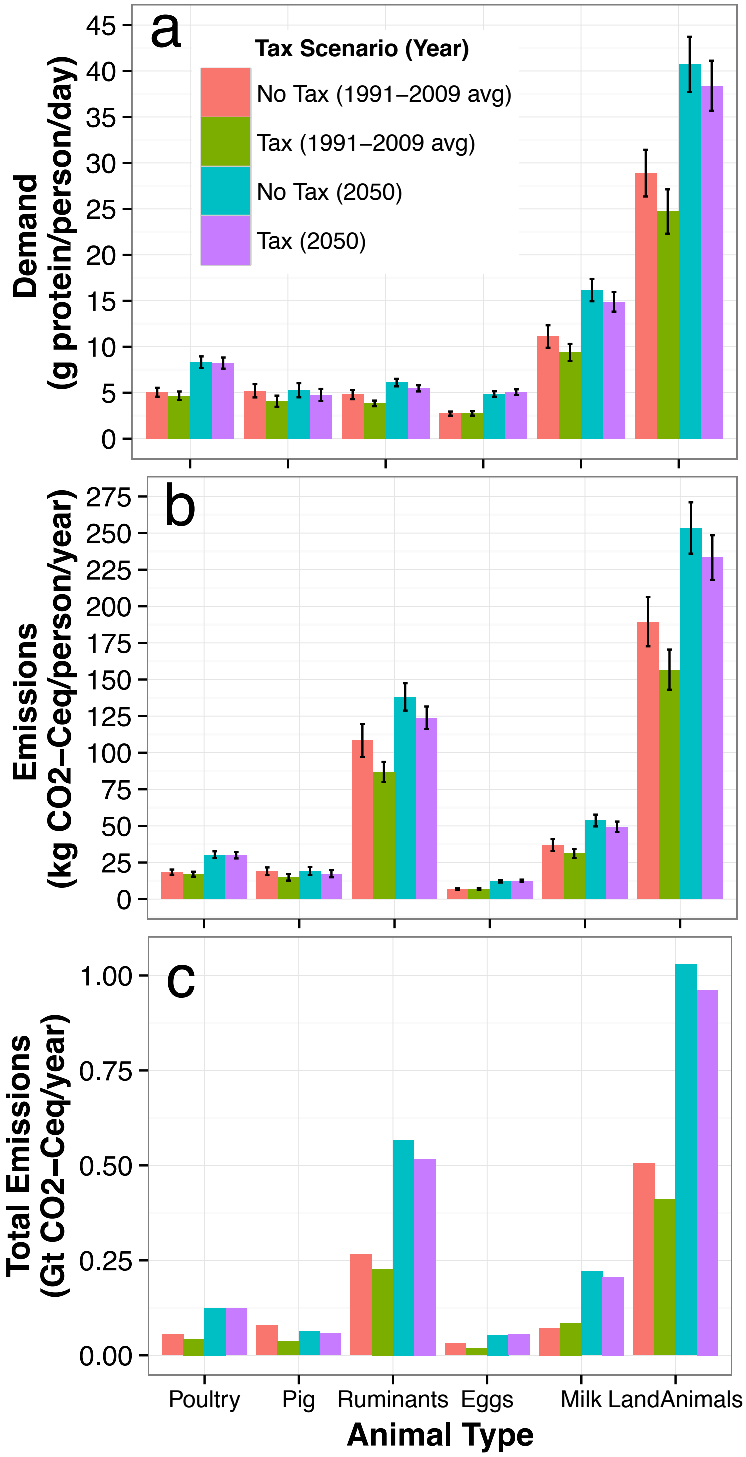

Figure 3. 1991-2009 across model current ("No Tax (1991-2009 avg)") and predicted **a.** per capita animal protein demand, **b.** per capita emissions, and **c.** total emissions. Error bars represent the standard error of the 54 countries around the mean.

As an additional exploration, we identified the multiple of a carbon tax that would hold per capita annual emissions constant at current levels in 2050. Doing so was far outside the predictive scope of the within model, given the minimal relationship between prices and emissions and therefore the magnitude of price increases required, but was found in the across model to require adding five times the carbon tax to prices. This would result in price increases ranging from 21.5% for eggs to 80% for ruminants (Table 3). Total emissions in 2050 would still grow to 0.807 Gt, 0.3 Gt (59.7%) above current levels. Holding total emissions constant to 2050 was outside the scope of the across model, but would be highly unlikely to occur via a carbon tax alone.

Discussion

The growth in income, urbanization, and population that is projected to occur towards 2050 will drastically increase the demands made of the world's food production systems. Meeting these demands while reducing agriculture's impact on the environment is one of humanity's greatest challenges (Foley et al. 2011; Tilman et al. 2011; Tilman and Clark 2014). A carbon tax could play a role in these efforts, but our research suggests that its role would not be great.

Agriculture and related land use change currently emit 10-12 Gt CO2 C eq per year, just under a quarter of all anthropogenic emissions (Smith et al. 2014). By 2050, these emissions may be 20.2 Gt (Bajzelj et al. 2014). The livestock sector alone is currently responsible for 7.1 Gt, 14.5% of all anthropogenic emissions (Gerber et al. 2013). If a carbon tax with the value of carbon at $133.37/tonne CO2 C eq in 1990 $ is applied to animal production emissions in our across model, we find that current (2050) emissions would decrease by 0.093 (0.068) Gt for our sample, which includes just over half the world population. If the entire world population were assumed to act like our sample, and if equivalent carbon savings were assumed to occur from land use change as from production emissions (Smith et al. 2014) but which we do not include in our model due to uncertainty about the emissions, then current (2050) emissions would decrease by 0.372

(0.272) Gt. These decreases are much smaller than current livestock emissions and the emissions decreases required to avoid dangerous climate impacts in 2050 (Bajzelj et al. 2014).

Within or across models

Despite the small magnitude of these emissions reductions, they are greater than those found to result in our within-country model from a carbon tax. Which model is thought to better represent the path that countries will take as their incomes, rates of urbanization, and prices change therefore determines whether a carbon tax appears promising as a potential mitigation lever. If countries are assumed to differ in static ways, as is likely over the short run, our more conservative within model may be a first good estimation and a carbon tax would appear to have minimal effect. But if across-country differences are not assumed to be static and countries instead may change throughout time, such as the assumption of Tilman et al. (2011) and Tilman and Clark (2014) that diets of low-income countries will become like diets of higher income countries as their incomes rise, our across-country model may better describe their long-run trajectories as incomes, urbanization and prices change.

While the conservative econometric practice may be to use a fixed effects analysis to assess trends only within countries, other analyses of the global food transition have made cross-sectional comparisons between countries (York and Gossard 2004; Tilman et al. 2011; Bonhommeau et al. 2013; Tilman and Clark 2014). A fixed effects analysis has the benefit of removing between-country variability that may correlate with the included variables but does not remove within-country variation over time that may correlate with the variables. Given the high likelihood of measurement error in generating annual average national prices for commodities, the within-country model likely underestimates the price elasticities. For example, another study of a carbon tax calculated emissions reductions using elasticities generated from both consumer-level and national-level data, and found a 2-4 times greater reduction using the consumer data (Edjabou and Smed 2013). An across-country analysis, on the other hand, facilitates modeling relationships across a broader range of values[ii] and accounts for within-country variation by averaging each response and predictor to a single mean value for each country across time. This allows for unobserved variables that correlate with the included variables across countries (Wooldridge 2012). Thus, our across-country analysis may overestimate the effect of prices, income and urbanization. Given the limitations of each model and the different time scales that they may represent, we report both within and across-country models, as lower and upper bounds.

While our across model may overestimate the effect of prices and our within model may underestimate it, both models project total emissions to increase at least 90% by 2050. The across model predicts lower increases in per capita demand to 2050 without a tax than the fixed model (40.9% vs. 45.5%), but due to compositional shifts in the type of animal protein demanded, greater increases in per capita emissions (33.8% vs. 30%) and total emissions (103.8% vs. 90%). Even with a carbon tax added in 2050, the across model projects total emissions to grow 90.3% from current levels, the same increase as under either scenario in the fixed effects model, where a carbon tax has no effect.

Price increases to 2050 independent of carbon tax

Prices for animal products have been projected to increase by 2050 in response to increases in meat and milk demand, biofuel use, and population, independent of any carbon tax (Rosegrant et al. 2013). Thus, we considered alternate conditions for scenarios 2 and 3, projecting to 2050 but assuming price increases of 45% for poultry, 54% for pork, 19% for ruminants, and 7% for milk, as well as 5% for eggs, which Rosegrant et al. (2013) did not include in their model, but which seemed a plausible, if conservative, increase. Given the greater size of these price increases compared to our carbon tax, this resulted in an increase of only 4.5 g (15%) in per capita demand to 2050 using our across model. This is similar to but smaller than the 23% increase of Rosegrant et al. (2013), and

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[ii] Income levels, prices, and many other variables have greater ranges across countries than within countries. Our data has an ~18 cent range in the mean price of a gram of animal protein across countries and only a ~2.5 cent mean range of prices within any individual country.

much smaller than our 11.8 g (40.9%) increase if prices are assumed to remain constant. However, in the alternate scenario 3, the addition of a carbon tax in 2050 would only lower per capita demand by 1.2g (3.7%), an even smaller reduction than the 2.3 g (6%) reduction in demand from a tax in our actual scenario 3. Using our fixed effects model to assess these alternate scenarios resulted in no effective decrease in demand from a carbon tax, just as with our actual scenarios 2 and 3 for the fixed effects model. We thus conclude that, while our models predict greater rises in demand to 2050 than are likely to occur if prices increase for additional reasons than a carbon tax, they consistently suggest that a carbon tax would have a little impact on demand currently or in 2050.

Saturation of demand at high income levels

The relationship of per capita income to demand for meat has been modeled to flatten out (Tilman and Clark 2014) or even curve downwards (Vranken et al. 2014) at high levels of income. This saturation is most apparent when demand for all meats is summed together, whereas we analyze the impact of price changes on demand independently for each type of animal protein in a system of equations with double-log transformations, a common econometric method (Nghiem et al. 2013). While this allows us to capture substitution effects arising from positive cross-price elasticities that could dampen the mitigating effect of a carbon tax, it does not completely account for the saturation. Therefore our projection of a 90%-103.8% increase in total annual livestock production emissions in 2050 compared to current levels is larger than the 80% and 77% increase in total emissions from all agriculture modeled by Tilman and Clark (2014) and Baljzejl et al (2014). However, livestock emissions within their models may have increased by greater than average rates, we compare to a 1991-2009 average as opposed to 2009 baseline, and we do not include India, all of which could increase the disparity. Nevertheless, our modeled per capita emissions increase of 33% is equivalent to the 32% increase in per capita emissions from all agriculture in Tilman and Clark (2014). Because our models do not account for the apparent saturation modeled by Tilman and Clark (2014), the absolute or percent increases we predict are less robust than our fairly consistent result of a small relative effect of a tax compared to the effect of rising income and urbanization.

For example, we created an ad-hoc semi-parametric model, which showed less of an increase in demand to 2050 than our models but found no effect of a tax. We fit a Gompertz 4P curve (after Tilman and Clark 2014) to the per capita daily demand for protein from all land animals. We used the equation to transform our per capita income values to a linear relationship with the demand. We then predicted demand for animals in a fixed effects regression including the transformed income values, urbanization, and an average price for land animal protein. From this equation, we predicted demand in 2050 under the scenario of constant prices, finding an increase in mean daily per capita protein demand of 8.1 g (28%), which is lower than the predicted 11.8 g (40.9%) increase of our across model and 13 g (45%) increase of our within model. Thus, our double-log models predict greater demand than a method accounting more for saturation of demand at high incomes, and our absolute and percentage predictions should be interpreted with care. However, our findings about the small effect of a carbon tax appear more robust; a tax at the mean SCC per g protein of the animal proteins (0.0026 1990 $) did not alter the 2050 prediction.

A second sensitivity analysis confirms that our conclusion about the relative ineffectiveness of a carbon tax does not differ greatly from what would be found in a model accounting more fully for the saturation. In fact, this sensitivity analysis matched the general results of both our within and across models. The majority of countries that have relatively flat relationships between per capita income and demand for animal protein fall into Economic Group A (Table 2), where incomes are above the ~15,000 1990 $ inflection point in Fig. 2 of Tilman and Clark (2014). We therefore split our across and within models each into two sets of seemingly unrelated regressions, one for the countries in group A and one for the countries in groups B, C, D, E, F, and China. We used these equations to model demand under our three scenarios: a carbon tax, income and urbanization growth to 2050, and income and urbanization growth to 2050 with a carbon tax. The predicted demand was at most ~1.5 g lower than the predicted demand of our actual models, and the magnitude of the reduction in demand due to the carbon tax was nearly identical to that found in our models: minimal in the within model and 13.65% in the across model, as compared to 14.5% in our actual across model. These results suggest that our double-log models at least approximate the saturating relationship of demand and income and confirm our findings of the low effectiveness of a carbon tax, based on the elasticities calculated from our data.

Sensitivity of elasticities

However, our calculated elasticities are a source of such uncertainty that our results should be interpreted with great care. So many of our fixed effects elasticities are not different from 0, and the impact of rising income and urbanization to 2050 so much greater than the mitigating effect of a carbon tax, that we do not conduct a sensitivity analysis. Instead, we compare to the literature. The elasticities in our fixed effects model are equivalent to those in another fixed effects analysis using the same producer price data (Fiala 2008) but are smaller than those in studies using other data to assess the mitigating effect of a carbon tax on livestock emissions (Wirsenius et al. 2011; Edjabou and Smed 2013; Sall and Gren 2015). The taxes levied in these studies are of similar rates to ours, and their elasticities are roughly equivalent to our across model elasticities; not surprisingly, their conclusions match those of our across model (17.3% reduction in current per capita emissions) more closely than our within model (1.9% reduction). They found that a carbon tax could reduce emissions from livestock by 12% (Sall and Gren 2015), 7% (Wirsenius et al. 2011), and 10.4-19.4% (Edjabou and Smed 2013).

In general, this field of study suffers from great uncertainty stemming from estimates of elasticities. A meta-analysis of 4,142 estimates of meat price elasticities found a median own-price elasticity of -0.77, slightly greater than the -0.54 mean own-price elasticity in our across model, but found a standard deviation of 1.28, highlighting just how much variation remains unexplained in estimates of elasticities (Gallet 2010). Exemplifying the implications of this uncertainty, Wirsenius et al. (2011) vary their elasticities +/- 50%, which they thought corresponded to the reported range in the literature, and determined that the range of different GHG reduction outcomes was equivalent to their entire modeled reduction from a carbon tax. Given the importance of estimates of price elasticities in determining outcomes of predictions and the high uncertainty surrounding the elasticities, this is an issue for our study as well as other studies into the same phenomenon.

Other social costs

The mean social cost of carbon estimate from Tol (2009), 133.37/tonne CO2 C eq in 1990 $, is more than 3.5 times greater than the 36.21 mode (converted to 1990 $). Our tax thus results in greater price increases than if the lower, more common, and more politically feasible estimate was used. However, other social costs from animal production could be included in a tax, raising its magnitude and therefore its impact. First among these are emissions from land use and land use change, which are responsible for just under half of worldwide agricultural emissions (Smith et al. 2014). Including these emissions could almost double the size of a carbon tax, especially if future land clearing were to occur in carbon-rich tropical forests, as was the case in the 1980s and 1990s (Gibbs et al. 2010).

Additional costs that could theoretically be incorporated into a tax on livestock include the loss in biodiversity from conversion of habitat, water used for livestock, pollution of waterways, and reduced health from non-communicable diseases associated with consumption of animal products. Including these costs could potentially increase the social cost of animal protein to five times the size of our carbon tax. If so, then price would appear to have more promise as a lever to reduce demand. However, the technical difficulties in determining the cost of each of these impacts and the political difficulties in transforming knowledge about social costs into policy action pose a formidable barrier to a tax incorporating these social costs.

Equity

Our research explores the potential impacts of a carbon tax levied on all nations, regardless of average per capita income levels. Future investigations into this topic should levy a tax in more equitable manner, such as only in high- to medium-income, food-secure nations (Nordgren 2012). However, by allowing poor nations to increase demand for animal protein, this would further reduce the magnitude of the mitigation of emissions, especially if 'leakage' of emissions occurred via a shift of production to unregulated locations (Key and Tallard 2012). One way to mitigate emissions from all nations with less negative impact on food security would be a revenue-neutral tax that subsidized consumption of environmentally beneficial or healthy foods with revenues from a carbon tax, as has been explored for the European Union (Edjabou and Smed 2013).

Other livestock co-products

Future work into the potential effect of a carbon tax on demand for animal protein should consider animal fats as well as the myriad other products and functions of animals, such as leather, wool, traction, savings, and insurance (Key and Tallard 2012). Doing so would provide a greater ability to assess the dynamics and determinants of demand for the animal-based foods and the potential unintended impacts of price changes. Including wool or skins, for example, would result in lower emissions estimates and therefore taxes per gram of ruminant protein, if emissions were divided between meat and the other products made from the animals.

Conclusions

Although it might seem that increasing prices of animal proteins through a carbon tax could be an effective mechanism to reduce livestock emissions, our study does not find strong or certain evidence of its potential. While preliminary and subject to limitations due to study design, as noted above, our within model results instead suggest that a carbon tax to mitigate greenhouse gas emissions from livestock would have negligible effects, while our across model suggests that a carbon tax would reduce current (2050) total emissions ~18% (6%). These decreases would not be sufficient on their own to mitigate current or projected emissions from livestock. Technical, educational, cultural, ethical, political and other approaches should all be employed to make meaningful reductions in demand for animal products today and into the future, as incomes, urbanization, and population continue to increase.

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Appendix

Supplementary Information

1. Identifying predictors of demand for animal protein
2. Additional creations

1. Identifying predictors of demand for animal protein

Variable Identification

Food demand patterns are influenced by factors at multiple scales, from individual decisions about which food to eat at which moment, to cultural differences at local, national or continental levels, to government policy and business choices at any of these scales, to economic and technological trends at a global scale. The dynamics at each of these scales sum to create, among other trends, a global transition towards animal-based foods over the past 50 years (Delgado 2003; Bonhommeau et al. 2013; Tilman and Clark 2014). To understand this global trend, we searched for potential predictors of demand for animal protein that were available at a national level from 1961-2009. We were searching for correlational relationships, although many of the predictors we considered have been or could be theorized to contribute causally to dietary change. Data availability limited the scope of the variables that could be considered. For example, data on food advertising, on national agricultural policies, and on religious changes over time were not found in readily available formats.

Over the nearly 50 year timescale covered by our data, the world has become ever more "globalized," with countries experiencing simultaneous geographic, economic, nutritional, technological, and demographic transitions whose progressions differ in timing from place to place but follow an overall pattern. Many of the indicators of these transitions are highly collinear, including: percentage urban population, per capita income, per capita value of international trade, agricultural yield, mean life expectancy, population growth rate, population age structure, and mean years of education among adults. Even though many of these variables were seen to correlate with and could plausibly have real-world relationships with demand, we had to remove many of them to avoid over-parameterization and multi-collinearity, which further limited the range of potential predictors considered.

Variable Selection

We created regression models with the average per capita daily demand for all land animal protein as a response and a variety of predictors, including: mean life expectancy, mean years of education, an index of political regime type on a continuum from democracy to autocracy, major episodes of political violence, value of international trade per capita, population density, per capita area in pasture and permanent meadows, per capita cropland, and Gini coefficient. We also included the constant terms: percentage of border that is coastline, climate zone, percentage Hindu, percentage Christian, and percentage Muslim. Through a combination of all-subsets regressions on portions of the dataset for which different variables were available and assessments of which predictors could plausibly have causal relationships with demand for animal protein, we settled on the predictors in Table S1. While many of the above predictors have statistically significant relationships when compared independently to demand for animal protein, their inconsistent data availability or less robust relationship to demand led us to exclude them.

Table S1. Model comparison. Standard errors are in parentheses. Fixed effects models report within R^2 and Driscoll-Kraay standard errors, which are robust to serial and cross-sectional correlation (Hoechle 2007).

	Dependent variable: LandAnimalsLog							
	Models							
	OLS	Across	Fixed	FullFixed	FullFixed91	FullFixed91Px	Fixed91Px	Across91Px
pcGDPLog	0.623***	0.675***	0.384***	0.298***	0.235***	0.235***	0.382***	0.385***
	(0.011)	(0.079)	(0.023)	(0.030)	(0.046)	(0.051)	(0.015)	(0.069)
UrbanPct	0.009***	0.007	0.012***	0.014***	-0.004	-0.004	0.003	0.009**
	(0.001)	(0.004)	(0.001)	(0.001)	(0.003)	(0.003)	(0.002)	(0.003)
Pop014Pct				-0.008***	-0.026***	-0.026***		
				(0.002)	(0.002)	(0.002)		
YieldLog				0.101***	-0.061***	-0.061***		
				(0.018)	(0.010)	(0.013)		
PasturePerCapLog				0.151***	0.034*	0.034*		
				(0.016)	(0.014)	(0.017)		
CropPerCapLog				0.020	0.009	0.009		
				(0.014)	(0.048)	(0.045)		
AnimalsPPLog						-0.0003	-0.003	-0.449***
						(0.018)	(0.023)	(0.117)
Constant	1.444***	1.486***						0.119
	(0.017)	(0.122)						(0.347)
Observations	4,397	91	4,397	4,397	724	724	724	54
Adjusted R^2	0.779	0.771	0.546	0.578	0.393	0.392	0.329	0.856

*p<0.05; **p<0.01; ***p<0.001

Model Selection

Per capita income and urbanization are the factors listed most often as drivers or correlates of the global dietary transition (Delgado 2003; York and Gossard 2004; Tilman et al. 2011; Reich 2014; Tilman and Clark 2014). Thus, we began by assessing the overall relationship between per capita demand for land animal protein and per capita income and urbanization over the period 1961-2009. In an ordinary least squares analysis (Table S1, OLS) urbanization and income alone explain a remarkable 77.9% of the variation in demand from 1961-2009. Income and demand are logged, so the coefficient of pcGDPLog is an elasticity. Thus, a one percent increase in per capita GDP relates to an increase of 0.623 percent in land animal protein demand. As urbanization is untransformed, a one unit increase in the predictor (an increase of one percentage point) relates to an increase in protein demand of ~100 times the coefficient, or 0.9 percent (Weisberg 2014). The magnitude of these relationships remains constant when analyzing means across nations (Across), although urbanization loses its significance. However, if country is included as a fixed effect (Fixed), as the results of a Hausman test suggest over a random effect or OLS model, the effect of income decreases by nearly half while the effect of urbanization increases slightly. This suggests that urbanization is a relatively stronger correlate within countries, while income is a relatively stronger correlate across countries. Urbanization and income explain just over half of the variation in animal protein demand within each country.

To explain a greater proportion of the variation in demand within each country over the period 1961-2009 we included additional variables (FullFixed). The FullFixed model explains only an additional 3% of the variation in demand compared to the Fixed model with just income and urbanization, reinforcing their utility as predictors. That said, while income and urbanization are good predictors, they are not the only plausible predictors. Many additional terms appeared as significant, with a one percentage point decrease in percentage of population age 0-14 corresponding to 0.8 percent higher demand, and higher yields and more pasture per capita corresponding to significant yet small increases in demand. Cropland per capita, while positively related to demand in all models, was never statistically significant - pasture per capita is a much more important predictor.

Running the same model in the period 1991- 2009 on the much smaller subset of countries with price data (Table 2) lowered the adjusted R^2 to ~0.4 and resulted in a number of minor changes to predictors (FullFixed91). The absolute magnitude of the coefficients of all the predictors decreased, with the exception of the coefficient of percentage of population age 0-14, which increased nearly threefold. Within this subset of countries, a one percentage point decrease in percentage population age 0-14 corresponds to an increase in demand of 2.6 percent. Interestingly, urbanization lost its significance as a predictor; within these countries population age structure appears to be a more important predictor. The sign on yield became negative, from which we determine that in this subset of countries, as well as overall, pasture per capita is the most robust agricultural predictor of demand.

Adding an average animal price (FullFixed91Px) caused no appreciable change to the models, as animal price was not a significant predictor of demand. This was surprising, as price is thought to relate very closely to demand for goods and a carbon tax raising the prices of livestock products based on their GHG emissions has been suggested as a potential emissions mitigation strategy (Nordgren 2012; Bajzelj et al. 2014). Its lack of significance here suggests that within these countries the average price of animal protein is not a good predictor of demand and therefore may not be an effective "lever" to raise through a carbon tax. Alternately, it suggests that producer prices are not good proxies for consumer prices.

To determine whether price had a weak effect that was being obscured due to collinearity with another predictor, we simplified the model so that it included only income, price and urbanization (Fixed91Px), a set of predictors previous studies have considered (Fiala 2008). Even in this simplified model, neither average price nor urbanization was a significant predictor. The lack of evidence supporting price as a correlate of animal protein demand in the period 1991-2009 within these countries confirms the use of income as a predictor of animal protein demand, and suggests at the inutility of price as a lever to reduce GHG emissions.

However, across-country variation in per capita GDP, urbanization and average animal price explains 85.6% of the variation in mean demand (Across91Px), a much greater percentage than the 32.9% of within-country variation in demand explained by the fixed effects analysis (Fixed91Px). The strength of income is remarkably consistent between the within and across analyses (coefficient of ~0.38), whereas the effect of urbanization increases threefold in the across model, to the same level seen in the OLS, where a one percentage-point increase in the extent of urbanization corresponds to a 0.9 percent increase in demand. Most importantly, in the context of assessing whether price may be a viable mechanism to reduce demand, price appears as a highly significant predictor, with a one percent increase in average price corresponding to a 0.45% reduction in demand. We further explore the relationships between urbanization, per capita income, prices and demand by expanding the average animal protein price term to the price of the five major types of protein from land animals, correspondingly expanding the response term to the demand for each of the five types of protein (see Results).

2. Additional creations

The following are other creations that were published during the master's degree.

Reich AH. 2014. "We eat only meat"- A comparison of (food) cultures in transition: Greenland and the Republic of Tyva. J. of Siberian Federal Univ. http://journal.sfu-kras.ru/en/article/16503/525

MinuteEarth videos created with the MinuteEarth team:

Title	**Date**	**Link**
Denizens of the Deep	8/31/13	https://youtu.be/pp7BZjJkc_8
How to Survive a Lightning Strike	9/9/13	https://youtu.be/eNxDgd3D_bU

The Biggest Organism on Earth	9/17/13	https://youtu.be/vWAA-SrrFUQ
The One That Got Away (Size Matters)	9/29/13	https://youtu.be/u9YOVuEQugE
Which Came First - The Rain or The Rainforest?	10/19/13	https://youtu.be/Y3OWgb0Bv-A
What is Skin For?	10/27/13	https://youtu.be/r8AYLGJuyvw
Why is All Sand the Same?	11/26/13	https://youtu.be/pxmHHoTPSKI
How to Make a Seashell - Just Add Water!	12/2/13	https://youtu.be/kmpzDfrqliU
What Happened To This Car?	12/9/13	https://youtu.be/4Uwxr42JqYQ
Birds that Hibernate in Lakes?!	12/16/13	https://youtu.be/ZPUYBsI7Pp0
How your dog can protect you before you're born	1/7/14	https://youtu.be/ex5y6OVVHe0
How do Trees Survive Winter?	1/27/14	https://youtu.be/d260CmZoxj8
Where Did Earth's Water Come From?	2/7/14	https://youtu.be/_LpgBvEPozk
Are any Animals Truly Monogamous?	2/14/14	https://youtu.be/bxQdLhOQf5c
Poop Transplants!	3/30/14	https://youtu.be/Dim7YXYlRm0
How To Date A Planet	4/25/14	https://youtu.be/YSau4HTNjkE
Ocean Confetti!	5/10/14	https://youtu.be/qVoFeELi_vQ
Invasion of the Yellow Crazy Ants!	6/2/14	https://youtu.be/tmztPktOfzs
The Secret Social Life of Plants	6/17/14	https://youtu.be/vk-12s7tB_Y
Why is it Hot Underground?	7/16/14	https://youtu.be/mOSpRzW2i_4
Why do Bats Transmit so many Diseases like Ebola?	8/14/14	https://youtu.be/Ao0dqJvH4a0
How to Build a Better City	8/19/14	https://youtu.be/TRb52O76HxQ
Why Do We Have More Boys Than Girls?	9/4/14	https://youtu.be/3IaYhG11ckA
How to Keep Elephants and Wolves Out of Your Yard	9/19/14	https://youtu.be/UY-mEGctbLw
Five Crazy Bridges For Animals	10/8/14	https://youtu.be/VjCJvn__N5c
Are These Butterflies The Same?	10/22/14	https://youtu.be/O4STc1r-nVs
Why Do Rivers Curve?	11/19/14	https://youtu.be/8a3r-cG8Wic
Why Do We Eat Spoiled Food?	12/18/14	https://youtu.be/9yswzITbAbA
Plate Tectonics Explained	1/13/15	https://youtu.be/kwfNGatxUJI
Why Poor Places Are More Diverse	1/22/15	https://youtu.be/mWVATekt4ZA
This Is Your Brain On Extreme Weather	2/17/15	https://youtu.be/cJCczZd7HVk
Why Do We Only See One Side of the Moon?	2/28/15	https://youtu.be/6jUpX7J7ySo

Why do Some Species Thrive in Cities?	3/24/15	https://youtu.be/4LDGzXpei8k
Why Don't Scavengers Get Sick?	3/31/15	https://youtu.be/GPJBw-TLYZQ
Why Are There Clouds?	4/21/15	https://youtu.be/QC2x_RRnk8E
Should We Let Pandas Go Extinct?	4/30/15	https://youtu.be/VEMtc1w4z6c
Rain's Dirty Little Secret	5/8/15	http://youtu.be/87v_9Bud7vw
How Do Greenhouse Gases Actually Work?	5/26/15	http://youtu.be/sTvqIijqvTg
Are We Really 99% Chimp?	6/11/15	http://youtu.be/IbY122CSC5w
Is Climate Change Just A Lot Of Hot Air?	6/18/15	http://youtu.be/nEQghbA3pLM
Do We Have to Get Old and Die?	6/29/15	http://youtu.be/Yc_VENHxLg0