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Displacement Risk in Agricultural Commodity Markets: The Impact of Plant-Based Meat

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Abstract

Plant-based meat is an innovative and sustainable type of food that has been received with enthusiasm by consumers and investors. It is also a threat for the demand of traditional meat, and for those crops used primarily as animal feed. In 2018, 59% of global corn and 83% of global soybean production were used as inputs for meat production. In this paper we consider plausible global plant-based meat adoption scenarios for 2030 and couple them with production, efficiency and price elasticity measures from the literature. We generate simulated corn and soybean negative demand shifts and their associated price change distributions, relative to a baseline scenario without plant-based meat. Expected (std. dev) declines for corn and soybean prices under low plant-based meat adoption scenarios are $-13\%(4\%)$ and $-22\%(7\%)$ respectively. For high adoption scenarios, corn and soybean declines are $-23\%(6\%)$ and $-38\%(9\%)$. These projections are economically very significant. Permanent shocks of this magnitude are comparable, but of opposite sign, to that caused by the ethanol mandate on the price of corn and reported in the literature. Corn and soybean producers, at the farm and regional level, are at risk of suffering from technological displacement.

Keywords: Long term risk; Agricultural commodities;

JEL codes: G13; G17; L11; Q4.

1. Introduction

The development of plant-based meat (PBM) has recently become headlines through the rapid growth of Beyond Meat and Impossible Foods. These firms are the most visible among those in the PBM industry which is emerging as a significant potential disruption to the traditional meat industry. Beyond Meat¹, which surged +163% in its initial public offering on May, 2019, has perfected the production of traditional meat substitutes directly from plants, enabling consumers to experience the sensory attributes of traditional meat while enjoying the nutritional and environmental benefits of eating a plant-based product. Beyond Meat’s plant-based proteins, which resemble chicken, sausages, burgers and beef, are currently sold at more than 58,000 restaurants and grocery stores in more than 10 countries. Another firm revolutionizing the meat industry is Impossible Foods,² founded in 2011. It has successfully improved its plant-based products’ taste to the point of making them indistinguishable from traditional ones. Its products are sold in over 17,000 restaurants in the U.S. and Asia, including Burger King Worldwide, and hundreds of American grocery stores. Impossible Foods has raised an estimated \$1.4 billion in funding as of August 2020. Also in 2020, Starbucks and McDonald’s started selling Beyond Meat products in Canada, and Walt Disney announced its partnership with Impossible Foods. Both companies are currently strengthening their technology platforms to offer more sustainable food alternatives that mimic steak, bacon, and fish. While Beyond Meat and Impossible Foods are high-profile innovators, nearly 150 plant-based food companies in the U.S. are contributing to the industry growth. Plant-based meats are a subset of non-traditional or alternative meats, which encompass novel protein products intended to reduce or replace animal meats’ production and consumption. The term comprises a variety of protein sources, ranging from plants, algae, insects and fungi

¹<https://www.beyondmeat.com/>

²<https://www.impossiblefoods.com/>

to in-vitro, clean or cultured meat (meat grown by farming cells directly, rather than via rearing and slaughtering an animal). Although some of them have not yet reached commercial status, the number of researchers, start-ups and investors focusing on them has boomed in the last years.

PBM has become a source of food that is rapidly gaining acceptance among consumers, since it is generally perceived as both healthy and beneficial for the environment. Its production requires significantly less land, energy and water than animal products. Environmental benefits are significant (Godfray et al. [2018], Tilman and Clark [2014], Nijdam et al. [2012], Nelson et al. [2016]). In addition, consumers concerned about animal treatment by the traditional meat industry are more comfortable with plant-based products. PBM also reduces antibiotics' resistance risks. Moreover, it contributes to world food security due to its flexibility and efficiency. As human population increases, there is growing interest in meat alternatives. By early 2021 non-traditional meats have the potential to significantly disrupt the traditional meat value chain. The partial replacement of animal meat by PBM would substantially diminish demand for crops currently used primarily as animal feed.

In this paper we perform a first-order quantitative analysis of the potential effects of a global consumption shift away from traditional meat and towards PBM, on corn and soybean producers. Using quantitative and qualitative information, we propose realistic scenarios for PBM adoption by 2030. Based on these, and on detailed information about animal feeding practices, we simulate the associated decrease in corn and soybean demand. Finally we estimate the impact on crop prices and output using supply and demand elasticities from the literature. Our simulations recognize the wide uncertainty that exists about the current and future values of microeconomic, behavioral and technical parameters that will determine the actual impact of PBM. We consider a low PBM adoption scenario where by 2030 a 2% to 6% of animal meat is replaced by PBM.

In this case, we find that the prices of corn and soybeans could plausibly experience a permanent price decline in the 10%–17% and 16%–29% ranges respectively, relative to prices in the absence of PBM. In a 5%–10% adoption scenario, the prices of corn and soybeans could decrease by 18%–29% and 29%–47% respectively. The decrease in demand for corn and soybean would likely be replaced by crops such as peas and lentils used as inputs in PBM. However, the plant mass required to produce a kilogram of PBM is much smaller than the mass of crop needed in animal feed for a kilogram of traditional meat. Moreover, regions best suited for corn and soybeans might not be those optimal for alternative crops. Therefore, corn and soybean producing regions, including states in the US Midwest and the central region of Argentina, would experience sizable negative shocks in local economic output due to technological displacement. Our measures are likely to underestimate the impact of widespread PBM adoption as we do not quantify its impact on the wider supply chain associated with corn and soybeans.

Our paper adopts a very simple simulation approach that transparently includes uncertainty about parameters in the economy. Our goal is to provide policy makers and industry participants with an early approximate measure of the displacement risk caused by PBM. To this end we are willing to sacrifice the power of proper econometric identification that can only be achieved after the fact. Our paper is related to earlier work. The U.S. government imposed a strong ethanol mandate in 2005. This fuel component is made primarily out of corn. Up to half of the corn output in the U.S. was allocated to ethanol production following the mandate. Roberts and Schlenker [2009, 2013] and Carter et al. [2017] estimated supply and demand elasticities for soybeans and corn, and used them to quantify the permanent impact of the ethanol mandate. These authors estimated an approximate 30% increase in the price of corn due to this additional demand. Wirsenius et al. [2010] scenarios show that both a 25% decrease in meat consumption per capita in developed regions and a 20% substitution of ruminant meat consumption with pork and

poultry at a global level, significantly decreases total agricultural area required for food production. Stehfest et al. [2009] analyzed partial and complete substitution of animal by plant proteins between 2010 and 2030, finding that under global mean production characteristics, the same amount of proteins from PBMs would require much less land than that used for beef and pork.

The paper is organized as follows. In Section 2 we present the framework to quantify the price impact of PBM on corn and soybean prices. Section 3 discusses quantitative and qualitative data that we use to build scenarios. Our simulation results are presented in Section 4. We conclude and discuss future research in Section 5.

2. The framework

We focus on the global market for corn and soybeans, which are used to produce animal feed. This, in turn, is used to produce different types of meats such as beef, pork and poultry. Table 1 displays actual and projected statistics for crops and meat markets [OECD, 2019]. Roughly 58% of corn and 88% of soybeans are used as animal feed, or as input for feed. Through crushing, soybeans are transformed into meal, at an approximate conversion ratio of 75% of bean weight, and oil. Wheat and rice, unlike corn and soybeans, are largely employed as human food and will not be the focus of this paper.

Figure 1 displays historical corn and soybean prices with yearly frequency. A very high correlation is apparent. The historical ratio between soybean and corn prices in the last fifty years had an average of 2.52 and has been in the $[2.00, 3.20]$ range. Such a strong correlation follows from the fact that these crops are, to some extent, substitutes: they are used for similar purposes (e.g. as feed), both are grown during the summer, and in similar regions (mainly in the U.S. Midwest, Argentina and Brazil).

We consider a basic model of yearly global crop supply and demand with constant elas-

Figure 1: Historical crop prices.

ties. We are interested in the long-term permanent effects of the adoption of PBM therefore we abstract from the possibility of storage which can smooth price variations and consumption in the short run but is unlikely to modify price levels in the long-run. Also, corn and soybeans do not last longer in storage than a couple of years, therefore we assume that negative demand shifts in 2030, even if perfectly forecastable, have no impact on current prices.

Supply S_{crop} and demand D_{crop} at long-run horizon T satisfy

$$\begin{aligned} \log(S_{crop}) &= a_{crop} + \beta_{crop} \log(P_{crop}) \\ \log(D_{crop}) &= b_{crop} + \gamma_{crop} \log(P_{crop}) \end{aligned} \tag{1}$$

where P_{crop} is the real price of crop and the β_{crop} and γ_{crop} coefficients are supply and demand elasticities respectively. In line with empirical evidence in Merener [2015] we assume that the markets for corn and soybeans are globally integrated, each aggregating

	2016–2018	Est. 2028	Est. 2030
Corn			
World production	1,128	1,311	1,344
Feed use	652	772	794
Wheat			
World production	752	838	856
Feed use	146	168	172
Soybean			
World production	353	411	423
Meal production	242	290	299
Beef			
World production (retail weight)	47.9	54.3	55.5
Pork			
World production (retail weight)	93.1	100.5	101.8
Poultry			
World production (ready to cook)	121.1	141.1	144.7

Table 1: World production statistics and projections for crops and meats in millions of metric tons. Source: OECD – FAO Agricultural Outlook 2019 – 2028 up to 2028, and linear projection for 2030.

global rather than local supply and demand. Global output and prices are set by matching supply and demand at each point in time.

Roberts and Schlenker [2009, 2013] and Carter et al. [2017] estimated supply and demand elasticities for soybeans and corn and then estimated the corn price impact of the ethanol mandate in the U.S. They attributed an approximate 30% corn price increase to the positive demand shift caused by the permanent government requirement that gasoline contain at least 10% of ethanol.

In this paper we perform a similar exercise, focusing on the potential decrease in the demand for corn and soybeans caused by a decrease in the demand for traditional meat.

In our setting, a shock that vertically shifts the crop demand curve by a percentage $\frac{\Delta D_{crop}}{D_{crop}} < 0$ leads through the equilibrium condition for (1) to a percentage price change of

$$\frac{\Delta P_{crop}}{P_{crop}} = \left(1 + \frac{\Delta D_{crop}}{D_{crop}}\right)^{\frac{1}{\beta_{crop} - \gamma_{crop}}} - 1. \quad (2)$$

In this paper we avoid an explicit model of supply and demand in the meat market in response to the emergence of PBM. We take as given a plausible range for the displacement of traditional meat by PBM, based on expert forecasts to be discussed in Section 3. We assume that the decrease in crop demand caused by the growth of alternative meats is determined by the amount of crop that will cease to be needed for feed by the adoption of PBM (PBM). Parameters and their definitions are as follows:

Parameter	Definition
$M_{beef}, M_{pork}, M_{poultry}$	global yearly tonnage of animal in the absence of PBM
$d_{beef}, d_{pork}, d_{poultry}$	% of animal meat to be replaced by PBM
$i_{beef}, i_{pork}, i_{poultry}$	% of animal meat produced by industrial feed methods
$f_{beef}, f_{pork}, f_{poultry}$	kgs of feed mix per kg of industrial animal meat
$c_{beef}, c_{pork}, c_{poultry}$	% of corn per kg of feed mix
$s_{beef}, s_{pork}, s_{poultry}$	% of soybean per kg of feed

Table 2: Model parameters and variables.

The tonnage of corn used in the production of beef in a baseline scenario without adoption of PBM is $M_{beef}i_{beef}f_{beef}c_{beef}$ and analogous expressions hold for other types of meats or crops. In the case of soybean we adjust by a factor of $1/0.75$ to reflect the fact that the feed mix actually contains soybean meal even if we work with tons of soybeans in our computations. The relative change in corn demand caused by the adoption of PBM is determined by the replacement shares $\{d_{beef}, d_{pork}, d_{poultry}\}$. Assuming that PBM is likely to replace industrial and non-industrial meat with equal likelihood, the demand shift associated to PBM is,

$$\begin{aligned}
\frac{\Delta D_{corn}}{D_{corn}} = -\frac{1}{M_{corn}} \quad [& d_{beef} M_{beef} i_{beef} f_{beef} C_{beef} \\
& + d_{pork} M_{pork} i_{pork} f_{pork} C_{pork} \\
& + d_{poultry} M_{poultry} i_{poultry} f_{poultry} C_{poultry}],
\end{aligned} \tag{3}$$

where M_{corn} is the yearly global tonnage of corn in the absence of PBM. An analogous expression holds for the impact of PBM on the soybean demand. Then, by using (3) as demand shift in (2) we can calculate the change in crop price caused by a change in meat demand.

The percentage change in crop global output M_{crop} in this setting is

$$\frac{\Delta M_{crop}}{M_{crop}} = \left(1 + \frac{\Delta D_{crop}}{D_{crop}} \right)^{\frac{\beta_{crop}}{\beta_{crop} - \gamma_{crop}}} - 1, \tag{4}$$

The value that each quantity on the right side of (3) will take at a distant horizon is uncertain. However, a probability distribution with sensible bounds, conditional of quantitative and qualitative information available at the time of writing this paper, can be plausibly attached to each quantity in Table 2 for the year 2030. Then, by sampling from these distributions, we are able to implement a simulation algorithm to infer the probability distribution of real crop price returns. This proceeds by generating a large number of samples for the quantities on the right side of (3) and mapping them to price changes through the algebraic expression in (2). This procedure generates a set of simulated samples of $\frac{\Delta P_{crop}}{P_{crop}}$. The price change distribution implied by these simulated outcomes will allow us to gauge the risk in crop markets associated to the diffusion of PBM. In our projections will consider two polar cases. In the first case we will simulate crop specific demand shocks and price changes, separately for corn and soybeans. This builds on the notion that corn and soybeans make different contributions to animal feed and therefore their prices might respond unequally to a meat demand shock. In

particular, the proportion of global soybeans used as feed is larger than that of corn, hence we would expect soybean prices to be more sensitive to innovations in the meat market. Also, as stated earlier, corn is primarily a source of calories while soybeans also add protein. However, running separate estimations is oblivious to the fact that corn and soybeans are substitutes to some degree, as suggested by their price dynamics in Figure 1. Therefore, in a second application of our simulation approach we aggregate corn and soybeans through their caloric content, as in Roberts and Schlenker [2009, 2013]. In this case, we obtain a simulated distribution for the change in the real price of calories in 2030 as a consequence of the development of PBM.

3. Data

3.1. Agriculture and meat production

Table 3 presents global estimates from the literature for the share of animal meat produced by industrial means, or feed-based methods, which rely heavily on corn and soybeans or their byproducts such as soybean meal. Industrial methods based on corn and soybeans are more prevalent in poultry and pork than in beef, where a large proportion of ruminants are fed grass and forage or use mixed systems. These estimates will inform our distributions for the parameters $\{i_{beef}, i_{pork}, i_{poultry}\}$ from Table 2.

	Beef	Pork	Poultry
Share of meat produced by industrial means			
Source: FAO [2017])	14.8 %	73.8 %	91.9 %
Source: Garnett et al. [2017]	7 %	76 %	87 %
Source: Herrero et al. [2013]	6 %	87 %	84 %
Mean ($\pm$ range/2)	9.3 ($\pm$ 4.4)%	79.0 ($\pm$ 6.6)%	87.6 ($\pm$ 4)%

Table 3: Statistics for animal meat produced by industrial means. FAO [2017], Garnett et al. [2017] and Herrero et al. [2013] show 14.8%, 7% and 6% of global beef production is feedlot (urban), and 52.2%, 64% and 61.6% is mixed, respectively. We adopt a conservative stance on the use of corn and soybeans in beef and leave out mixed production.

Table 4 presents estimates from the literature for the amount of feed required per kg. of animal meat, and for the composition of feed in terms of corn, soybean and others. As we focus on the potential change in crop demand for feed, we evaluate the ability of different species to transform feed into edible meat. This is (Wilkinson [2011]) a very common expression of efficiency of feed use in non-ruminant livestock systems. Our feed conversion rates are the averages of four expert estimations across different countries and industrial production systems. Table 4 informs the distribution of parameters $\{f_{beef}, f_{pork}, f_{poultry}\}$, $\{c_{beef}, c_{pork}, c_{poultry}\}$ and $\{s_{beef}, s_{pork}, s_{poultry}\}$ in Table 2. Table 4 shows variability in the estimates of conversion rates from animal feed into edible products. Poultry is the most efficient meat in that it uses the smallest amount of feed per kilogram of meat. The bottom panel in Table 4 presents estimates of the proportion of corn and soybean or its byproducts in the feed of ruminants, pork and poultry. The relative contribution of corn and soybeans varies across meat types. We abstract in this paper from explicitly considering the variability in feed conversion rates across geographies and as a function of crops’ relative prices.

	Beef	Pork	Poultry
Kgs of feed per kgs of edible meat			
Source: Smil [2002]	25	9	4.5
Source: Shepon et al. [2016]	36	6	4.2
Source: Alexander et al. [2016]	25	6.4	3.3
Source: Kumar et al. [2017]	24	6.2	3.1
Mean ($\pm$ range/2)	27.5 ($\pm$ 6)	6.9 ($\pm$ 1.5)	3.8 ($\pm$ 0.7)
% of corn in feed mix			
Source: Flanders and Gillespie [2015]	0.30 ($\pm$ 0.15)%	0.60 ($\pm$ 0.15)%	0.60 ($\pm$ 0.15)%
% of soy meal in feed mix			
Source: Flanders and Gillespie [2015]	0.07 ($\pm$ 0.07)%	0.20 ($\pm$ 0.10)%	0.30 ($\pm$ 0.10)%

Table 4: Efficiency and production technologies for various kinds of meat.

For a consistency check of the estimates in Tables 3 and 4 we compute the total amount of corn and soybeans used for feed in meat production. We use

$$\begin{aligned}
\text{Corn feed for meat} &= M_{beef} * i_{beef} * f_{beef} * c_{beef} \\
&+ M_{pork} * i_{pork} * f_{pork} * c_{pork} \\
&+ M_{poultry} * i_{poultry} * f_{poultry} * c_{poultry},
\end{aligned} \tag{5}$$

and a similar expression for soybean. Estimates for M_{beef} , M_{pork} , $M_{poultry}$ are taken from the first column in Table 1 and those for i , f , c from Table 2. By (5) we obtain 307 million tons of soybean and 581 million tons of corn. These are about 12% lower than the 353 and 652 million tons of soybean and corn used for feed reported in Table 1. Discrepancies might be due to the fact that we are only including feedlot beef in our estimation while in reality mixed feeding systems also use corn and soybean meal to some degree. Dairy and layer hens also consume significant amounts of corn and soybean products but are not sources of meat and therefore add to the 12% gap reported above.

In the absence of PBM, traditional meat production is expected to continue growing over the next decade ([OECD, 2019]), due to sustained demand and rising incomes. Poultry production will follow growth in animal numbers (which is projected higher in emerging countries), while intensification and yield improvement will lead pork and beef output increase. By 2028, beef production is expected to expand by about 9 million tons, with Latin America and the U.S. representing more than half of global growth. Developing countries are expected to account for 72% of the additional production. Pork production is expected to grow by 11 million tons by 2028, with China accounting for more than 40% of global growth and Latin America increasing its production share. Global poultry production is expected to grow by 20 million tons, roughly half of the total growth in animal meat until 2028. This bias is driven by its rising popularity, as well as its high feed conversion ratio and low costs. China and Latin America are expected to drive this global expansion.

The decrease in crop consumption due to lower feed demand could be mitigated in part by agricultural production focused on PBM. Although detailed recipes for plant-based commercial products are not available, we can approximate their requirements. Beyond Meat’s burger uses proteins from peas, beans and rice. It also contains coconut oil, cocoa butter and minimal amounts of other ingredients like potato starch, natural flavor, yeast extract, salt, and beet juice extract. These burgers are made without GMOs, soy, or gluten. Impossible Foods uses soy and potato protein, coconut and sunflower oil to give the burger fat, heme (a molecule that contributes to its animal-like taste) and small quantities of other ingredients as binders. Since soybean is Impossible Burger’s second main ingredient,³ and the protein weight in a typical hamburger is 20g per 114g of meat, a plausible range of soybean use per kg of PBM ranges then between zero and 0.5 of its mass. This is to be compared with the feed conversion ratios in Table 2, which range between 3.8 for poultry to 27.5 for beef. Therefore, the decrease in the demand for corn and soybeans for animal feed would not be mitigated to a significant extent by the use of these crops in PBM. Moreover, as the plant-based industry grows and competition increases, plant protein sources are starting to diversify. There are already different proteins’ being tested and commercialized. The demand for peas and lentils in 2028 from this industry is expected to see a large increase relative to their current market size.

3.2. The rate of adoption of plant-based meat

The PBM market will likely grow at different speeds across regions due to diverse consumption patterns, demographics, production possibilities, technological capabilities, and regulations, among other factors. Nevertheless, it is likely that first movers’ profits will increase competition and make PBM available and affordable globally in the medium term. Market growth projections are abundant and diverse. Thus, we consider a broad

³Private communication with the company

set of qualitative and quantitative indicators to inform our simulations.

a) Consumer appetite for plant-based meat

Meat occupies a central position in food culture, holds a traditional status in many societies, is generally perceived as healthy and has unique sensory properties. Thus, any reduction in meat consumption will have to overcome both social and individual barriers. Although PBM companies' sales show the main adoption barrier - the relative unfamiliarity and low sensory appeal (Hoek et al. [2011]) - is being surpassed, there are many other consumption determinants: relative prices, culture and religion, current meat-eating habits, health consciousness and nutritional knowledge, environmental concerns, animal treatment considerations, and individual preferences.. The literature has found that consumers who are younger, female, more educated, less conservative, and from urban areas are more likely to reduce their meat intake than individuals with the opposite characteristics.⁴ This paves the way to a gradual decrease in traditional meat consumption led by generational change. Additionally, there is evidence backing PBM companies' marketing campaigns' effectiveness. First, emphasizing their relative environmental advantages is fruitful because people with higher environmental impact perception are more likely to consume meat substitutes.⁵ According to The Nielsen Company [2019], 62% of U.S. consumers are willing to reduce meat consumption due to environmental concerns, 43% would replace meat protein with plant-based protein, and 22% would become vegetarian or vegan in order to effect positive change. In Europe, 58% of consumers are willing to change their consumption habits to support sustainability. Still, consumers are not fully aware of the meat industry's environmental impact.⁶ Second, PBM companies have generally chosen to make their products available next to

⁴Apostolidis and McLeay [2016], Hartmann and Siegrist [2017, 2019], Graça et al. [2015b,a]

⁵Hartmann and Siegrist [2019], Slade [2018], The Nielsen Company [2019, 2020]

⁶Hartmann and Siegrist [2017], De Boer et al. [2016], Panzone et al. [2016]

their animal-counterparts. This is in line with companies' targeted market, known as "flexitarians" (meat-eaters cutting down on their consumption levels due to diverse reasons), who have been increasing their share among meat-consumers. In a Euromonitor International global survey Bagul [2020], flexitarians are estimated at around 21–24% of respondents (n=20,166). In the European context (n=410), Graça et al. [2015b] cluster analysis shows that around one third of their sample is consuming alternative meats, in accordance with other studies estimating a quarter to a third of flexitarian respondents. Moreover, Hartmann and Siegrist [2019] found a negative statistically significant correlation between meat and PBM consumption in Switzerland, showing meat substitution is affecting traditional meat's demand. Correlations were -0.18 (n=5,500) and -0.26, when considering meat substitutes consumers' only (n=1,260). In the U.S., Bryant et al. [2019] hypothetical consumption study found a 33% of respondents were very likely to purchase PBM, with even higher acceptance in China and India (62% in both countries). The International Food Information Council Foundation latest survey (n=1,000) shows 49% of American respondents have tried plant-based products, with men (53%) more likely to try them than women (44%). In a hypothetical choices study (n=533), Slade [2018] predicted that if prices were equal, two thirds of individuals would buy a beef burger, 21% a plant-based burger, and 11% a cultured meat burger (with 4% making no purchase). This can be understood as a lower bound for alternative meats' consumption, because although respondents were told that all burgers tasted the same, only 8% declared to have fully believed this. The study results suggest that PBM's share of the meat market could range from 14% (when priced \$1 more than regular burgers) to 24% (with no available cultured meat supply). In sum, consumer appetite for PBM is already economically significant and growing, driven by secular trends.

b) Recent plant-based market growth

Plant-based food retail sales are growing rapidly, while sales of many conventional animal products stagnate or decline. Moving to the meat industry, Barclays Research [2019a] estimates the global alternative meat market at 14 billion dollars (about 1% of the world's 1.4 trillion meat market). In the U.S., their estimated market share rises to 5% of the traditional meat industry. Data for PBM household penetration in the U.S. ranges from 14 to 21.6%,⁷ meaning that at least approximately 18 million households have bought PBM. Concerning companies' sales, Beyond Meat had annual revenues of \$32.6, \$87.9, \$297.9 and \$407 millions in the 2017-2020 period. The firm's international revenues share has also increased, from 1% to 16% in that period. Sales figures for Impossible Foods are non public but its most recent financing round values the company at \$4 billion in a strongly upward trajectory. As a whole, sales of PBM in the US in 2020 were in the vicinity of \$1.4 billion, or about 2.7% of all retail packaged meat sales.

In addition, established food industry leaders are entering this market. Nestlé renovated a facility to produce its pea-based "Incredible burger", launched a line of plant-based deli meats and, in 2020, announced plans to build a \$100 million plant-based food plant in China, to satisfy the country's demand.⁸ Kellogg Co., Kroger Co., Conagra Brands Inc., Hormel Foods Corp. and Tyson Foods Inc. are also introducing their own plant-based products.⁹

c) Benchmark industry evolution

The alternative dairy market provides a relevant medium term-growth benchmark for PBM market, since both are substituting mainstream staple products. Also, both mer-

⁷14% is estimated by The Food Industry Association & IRI (2020), representing a 8.5% increase from 2018 level of 12.9%. The upper bound, 21.6%, is from Nielsen Homescan, 52 weeks ended March 23, 2019, and implies a 1.6% increase from 2018.

⁸<https://thebeet.com/nestle-announces-plans-to-open-100-billion-plant-based-food-factory-in-china/>; <https://fortune.com/2020/05/21/nestle-plant-based-meat-factory-china/>

⁹<https://www.nestle.com/media/news/nestle-launch-plant-based-sausages-europe-us>, <https://www.tysonfoods.com/news/news-releases/2019/6/tyson-foods-unveils-alternative-protein-products-and-new-raised-rooted-r>

chandise products alongside their animal counterparts, have similar target markets and sales' trends, and intend to surpass the traditional product's taste and quality. Milk is by quantity, globally and in most regions, the most important livestock product. The American plant-based milk¹⁰ category is worth 2 billion, and accounts for 40% of the total plant-based food market, and about 14% of the dairy milk market. Plant-based milk has a household penetration rate of 41.3% in the U.S., while PBM has a rate of 14%. Barclays Research [2019b] shows that plant-based dairy penetration in recent adopters (France and Italy) is growing twice as fast as it did in mature markets (Germany and the U.S.).

All studies projected Asia Pacific as the fastest growing region in coming years for the alternative dairy market. The same view prevails among PBM companies, highlighting China's potential as the fastest growing meat consumer country, after its 15% PBM annual sales growth rates since 2014.

d) Industry projections

To the best of our knowledge, econometrically rigorous forecasts of PBM growth are not available in the academic literature. We let our scenario construction be informed by industry participants who are keen to anticipate future trends and produce forecasts based on their detailed institutional knowledge.

Investment firm UBS [2019] projected that the PBM market will grow by from \$4.6 billion in 2018 to \$85 billion in annual sales by 2030, a CAGR of 28%, as penetration rates increase from 0.4% to 6%. Euromonitor (2019) four-year outlook annual growth forecasts vary between 6.8% and 9.4% CAGR to 2025. The firm expects the market for meat alternatives in both Europe and America to double by 2022, since its demand has grown in both regions more than 30% in the past two years. Gerhardt et al. [2019], for AT

¹⁰Plant-based milk is led by almond (65% of dollar sales in 2019), soy (around 10%) and oat milk (the fastest-growing category).

Kearney, projected that by 2030, 18% of consumed meat-products will be plant-based replacements, with cultured meat gaining even bigger share by 2040. After Beyond Meat's IPO in 2019, banking analysts at J.P. Morgan and Barclays agreed that the PBM sector could reach a 10% share of the global meat market over the next 15 years. Barclays Research [2019a] estimates that the alternative meat market will grow from around 1% of the global market share in 2019 to 10% in 2029 with US\$140 billion in market share. J.P.Morgan, assuming that two-thirds of meat varieties could be replaced by plant-based options and with this category share topping out at 10%, modeled a total addressable market for PBM of \$100 billion in 15 years. Jefferies predicted a market annual global revenue of \$240 billion by 2040, and that it could reach 9% of the estimated \$2.7 trillion global meat market by 2040 (The Economist [2019]). Analysts coincide in Asia experiencing exponential growth in demand, driven by rising disposable income and consumer interest.

In summary, analyses from industry participants suggest that the market for PBM will continue to expand at very healthy rates under growing demand. The non-scientific but significant consensus among industry analyses discussed above points toward a plausible market share of PBMs by 2030 in the 2% to 10% range. This range is consistent with a 2020 share in the 1% to 2% and CAGRs between 6% to 18%.

e) Plant-based meat price and production costs

Beyond Meat and Impossible Foods' products are currently priced as premium products both in restaurants and in retail sales. Although there is evidence that current consumers are less price conscious than others,¹¹ in order to continue their sales' growth, companies need to be price competitive with traditional meat. Citing the benchmark plant-based milk market again, it is remarkable that it already commands a 13% market share in the

¹¹Slade [2018]

U.S., despite a large price premium and a different taste profile. Price is a clear barrier for PBM reaching mass markets in emerging countries, which are expected to lead the increase in meat consumption. Producers are fully aware that both good taste and a decreasing price dynamics are needed to sustain PBM adoption growth. Both leading companies are actively working to reach price parity and undercut the price of traditional meat, to increase their market share. In 2020, Burger King added the Impossible sandwich to its two-for-\$6 promotional menu to entice additional customers, and Impossible Foods announced a 15% average cut in prices for U.S. distributors. Beyond Meat has stated it intends to reach price parity in at least one of their product categories by 2024.¹² As with most new technologies, costs are likely to fall as the industry achieves economies of scale. Large efficiency gains will be likely once firms reach a scale where they can procure optimized raw materials rather than simply using preexisting crops. A per unit cost decrease will also be likely in terms of infrastructure, logistics and distribution. And competition should also significantly drive prices down in a relatively short term, as traditional meat leading companies are getting into the alternative meats' business, targeting competitive prices too (12 EUR/kg).¹³ In addition, large crop producers such as Cargill and Roquette are broadening their portfolio of alternative proteins to supply PBM production. In January 2020, Beyond Meat announced a multi-year pea protein supply agreement with Roquette which significantly increases the amount of pea protein to be provided over the next three years as compared to 2019. Cargill has invested \$100 million in a joint venture with Puris for pea protein ingredients, to at least double its production by 2020, in response to growing demand. In 2020, Cargill launched its own plant based brand (PlantEver) in China, after a successful product trial with KFC. The company plans to continue innovating, benefiting from its supply chain, scale and

¹²<https://www.bloomberg.com/news/articles/2020-03-03/impossible-foods-cuts-beef-price-by-15-for-its-distributors>

¹³Private communication with Euromonitor International

formulation capabilities. Nevertheless, the rising cost of scarce specific inputs for PBM products is a significant risk faced by the nascent industry, as well as potential regulatory restrictions and health impacts of additives which make their products more appealing to consumer tastes.

Surveys on consumer appetite, benchmark industry’s evolution, recent industry growth, analyst projections, all suggest that growth in the PBM sector will remain plausibly very strong over the next decade. Although these projections lack scientific rigor, they unanimously point towards strong growth. In the remainder of this paper we assume that by 2030, the share of PBM will belong in the 2% to 10% range of global meat output.

3.3. Elasticities

	Elast. of supply	Elast. of demand	Multiplier
Source: Roberts [2009], for calories	0.106	-0.039	[4.7,13.2]
Std. Error	(0.029)	(0.021)	
Source: Roberts [2013], for calories	0.112	-0.062	[4.3, 8.5]
Std. Error	(0.020)	(0.022)	

Table 5: Supply and demand price elasticities for calories and associated price multiplier.

In order to map the impact of changes on crops demand on crop prices, we gather appropriate elasticities from the literature. These are shown in Table 3. Roberts and Schlenker [2009, 2013] estimated supply and demand elasticities for crops, with focus on corn, rice, soybeans and wheat, which in total carry about 75% of the calories in global food production. Using global data between 1960 and 2007 these papers took advantage of yield and weather shocks, and variations in inventories with yearly frequency. Their elasticity estimates, based on aggregating calories from different crops, and (2) were transformed into multipliers to estimate the percentage price change in response to a permanent demand shock. Roberts and Schlenker [2013] performed a wide variety of

estimation exercises. Their strongest estimates in terms of identification are those for calories. Elasticity estimates for individual crops have much wider confidence intervals. For corn, Roberts and Schlenker [2013] find multipliers in the range already found for calories. For soybeans, their results are not significant enough to be conclusive. In our exercises we use the sharpest estimates from Roberts and Schlenker [2013] for calories, and choose to extrapolate their applicability to corn and soybeans individually. This is clearly a limitation of this exercise. A mitigating factor for this issue is the fact that very unequal price impacts on corn vs soybeans would be limited by substitution by consumers in the short run and by planting decisions in the long run. Based on these elasticities, a 30% to 35% corn price increase was attributed to ethanol-based higher demand in the aftermath of the Energy Policy Act of 2005. Furthermore, Roberts and Schlenker [2013] found that these estimates implied a 180 USD billion loss in consumer surplus by the higher cost of food, and a net benefit for commodity exporters. In related work, Carter et al. [2017] estimated a 29% long-run and scalable price increase in response to a 1.3 billion bushels of extra corn demand cause by the ethanol mandate. This demand shock was equivalent to 33 million tons, or approximately 4.6% of the 716 million tons of global corn output in 2007. Therefore, Carter et al. [2017] estimated a price multiplier around 6.3, well within the range identified by Roberts and Schlenker [2009] and Roberts and Schlenker [2013].

4. Simulation results

We simulate the distribution of percentage price changes for calories, corn and soybeans, for the year 2030. These are caused by negative demand shifts on a baseline production scenario for 2030 from OECD FAO in Table 1 which did not incorporate significant growth of PBM. Therefore, our results are to be interpreted as price changes relative to a baseline

case without PBM. We consider different scenarios defined by the degree of adoption of each kind of plant based meat, $D = \{d_{beef}, d_{pork}, d_{poultry}\}$, replacing animal meat. For each scenario we consider 500,000 independent realizations of industry parameters, of which we have four sets:

$$I = \{i_{beef}, i_{pork}, i_{poultry}\}$$

$$F = \{f_{beef}, f_{pork}, f_{poultry}\}$$

$$C = \{c_{beef}, c_{pork}, c_{poultry}\}$$

$$S = \{s_{beef}, s_{pork}, s_{poultry}\}$$

Each realization requires sampling parameter values from 12-dimensional multivariate distribution. In Table 6 we assume that the unconditional distribution of each parameter is a uniform distribution within economically wide ranges in Tables 3 and 4. In Table 7 we assume normally distributed parameters for a robustness comparison vs the uniform case.

	Beef	Pork	Poultry
% of industrial animal meat $i_{beef}, i_{pork}, i_{poultry}$	U[0.05, 0.14]	U[0.72, 0.86]	U[0.84, 0.92]
Kgs of feed per kgs of meat $f_{beef}, f_{pork}, f_{poultry}$	U[21.5, 33.5]	U[5.4, 8.4]	U[3.1, 4.5]
% of feed provided by corn $c_{beef}, c_{pork}, c_{poultry}$	U[0.15, 0.45]	U[0.45, 0.75]	U[0.45, 0.75]
% of feed provided by soybean $s_{beef}, s_{pork}, s_{poultry}$	U[0.0, 0.14]	U[0.10, 0.30]	U[0.20, 0.40]
Multiplier	U[4.3, 8.5]	U[4.3, 8.5]	U[4.3, 8.5]

Table 6: Uniform distributions $U[lowerend, upperend]$ for industry parameters based on ranges in Tables 3 and 4.

We assume that the main technological innovation between 2020 and 2030 in the global meat domain will be the adoption of plant based meat (the continuing increase in meat

	Beef	Pork	Poultry
% of industrial animal meat $i_{beef}, i_{pork}, i_{poultry}$	N[0.095, 0.045]	N[0.79, 0.07]	U[0.88, 0.04]
Kgs of feed per kgs of meat $f_{beef}, f_{pork}, f_{poultry}$	N[27.5, 0.06]	N[6.9, 1.5]	N[3.8, 0.7]
% of feed provided by corn $c_{beef}, c_{pork}, c_{poultry}$	N[0.30, 0.15]	N[0.60, 0.15]	N[0.60, 0.15]
% of feed provided by soybean $s_{beef}, s_{pork}, s_{poultry}$	N[0.07, 0.07]	N[0.20, 0.10]	N[0.30, 0.20]
Multiplier	N[6.4, 2.1]	N[6.4, 2.1]	N[6.4, 2.1]

Table 7: Normal distributions $N[mean, stdev] = N[(upperend + lowerend)/2, (upperend - lowerend)/2]$ for industry parameters based on ranges in Tables 3 and 4.

demand from Asia is already included in the baseline production estimate in Table 1). Focus on PBM is consistent with the relatively slow rate of change in the degree of industrialization of animal meat production (I), gains in efficiency through the reduction of the amount of feed per kg. of animal meat (F) and changes in the composition of the mix in terms of corn (C) and soybean (S) between 2010 and 2020. The uncertainty in parameter values in Tables 6 and 7 represents primarily our imperfect knowledge about the current values of these parameters in 2020, rather than simply uncertainty about the evolution of these parameters in a 10 year horizon. Under this interpretation, we assume that stochastic values of the parameters within a single realization in our simulation are all independent from each other. On longer horizons it would be appropriate to take into account the future evolution of the degree of industrialization of animal meat production (likely increasing) and the evolution of the amount of feed per kg. of meat (likely decreasing), among other considerations. Our simulations contemplate two families of scenarios: low plan-based meat adoption, defined as a 2% to 6% range of substitution of animal meat, and a high adoption regime, defined as a 5% to 10% range of substitution. Given the growth dynamics described in Section 3, these seem plausible scenarios.

Meat type PBM adoption	Beef d_{beef}	Pork d_{pork}	Poultry $d_{poultry}$	Calories price var
Beef, low PBM	U[0.02,0.06]	0	0	-0.014 (0.006)
Beef, high PBM	U[0.05,0.10]	0	0	-0.021 (0.009)
Pork, low PBM	0	U[0.02,0.06]	0	-0.079 (0.029)
Pork, high PBM	0	U[0.05,0.10]	0	-0.140 (0.043)
Poultry, low PBM	0	0	U[0.02,0.06]	-0.081 (0.029)
Poultry, high PBM	0	0	U[0.05,0.10]	-0.144 (0.042)
All meats, low PBM	U[0.02,0.06]	U[0.02,0.06]	U[0.02,0.06]	-0.158 (0.043)
All meats, high PBM	U[0.05,0.10]	U[0.05,0.10]	U[0.05,0.10]	-0.274 (0.062)

Table 8: Plant based meat adoption scenarios. Uniformly distributed shifts [*lowerend*, *upperend*]. Percentage calorie price change in 2030 relative to base case without PBM.

In Table 8 we present summary statistics for the distributions of price returns aggregating corn and soybeans by their caloric content. We show the effect of PBM adoption for individual types of meats and for meats in general. A decrease in the demand of animal beef has a relatively minor effect on prices. However, the introduction of plant-based substitutes for pork and poultry may plausibly lead to a price decrease for crops in the 20% to 30% range. Tables 9 and 10 show the impact of PBM on prices of corn and soybean separately. Tables 9 and 10 differ in the shape of their underlying distributions, uniform and normal respectively. Numerical results are very similar and indicate that the distributions' means determine price impact. The impact of PBM is larger for soybeans than it is for corn. This is consistent with the higher degree of utilization of soybeans in animal feed. In addition, the differences in the composition of feed mix in pork vs poultry is reflected in the fact that substitution of poultry has the maximal impact on soybean

prices. Overall, widespread adoption of PBM may lead to a decrease of 23% decrease in the price of corn, and 38% in the price of soybeans. Although very large, these numbers are comparable in magnitude to the impact of the ethanol mandate in 2007. On the other hand, in particular for soybeans, nonlinear effects, not captured in our simulations are likely to appear for such a large permanent shift.

Meat type PBM adoption	Beef d_{beef}	Pork d_{pork}	Poultry $d_{poultry}$	Corn price var	Soybean price var
Beef, low PBM	U[0.02,0.06]	0	0	-0.013 (0.006)	-0.015 (0.007)
Beef, high PBM	U[0.05,0.10]	0	0	-0.021 (0.009)	-0.022 (0.013)
Pork, low PBM	0	U[0.02,0.06]	0	-0.072 (0.027)	-0.103 (0.046)
Pork, high PBM	0	U[0.05,0.10]	0	-0.126 (0.039)	-0.181 (0.068)
Poultry, low PBM	0	0	U[0.02,0.06]	-0.063 (0.023)	-0.131 (0.050)
Poultry, high PBM	0	0	U[0.05,0.10]	-0.111 (0.034)	-0.228 (0.070)
All meats, low PBM	U[0.02,0.06]	U[0.02,0.06]	U[0.02,0.06]	-0.134 (0.037)	-0.224 (0.066)
All meats, high PBM	U[0.05,0.10]	U[0.05,0.10]	U[0.05,0.10]	-0.234 (0.055)	-0.380 (0.090)

Table 9: Plant based meat adoption scenarios. Uniformly distributed shifts [*lowerend*, *upperend*]. Percentage corn and soybean price change in 2030 relative to base case without PBM.

The magnitude of the estimated price changes would have strong implications at the farm level and, possibly, at a macroeconomic level for certain regions that are particularly dependent on agricultural commodities. In Table 11 we present a first order estimate of the impact of PBM adoption on the value of corn and soybeans output for certain regions. We are keeping produced quantities constant although in reality these are likely to fall as well in response to lower prices. Allocating the decrease in global output across regions would depend on the spatial distribution of costs and margins. By keeping physical

Meat type PBM adoption	Beef d_{beef}	Pork d_{pork}	Poultry $d_{poultry}$	Corn price	Soybean price
Beef, low PBM	N[0.04,0.02]	0	0	-0.014 (0.010)	-0.015 (0.014)
Beef, high PBM	N[0.075,0.025]	0	0	-0.021 (0.016)	-0.032 (0.023)
Pork, low PBM	0	N[0.04,0.02]	0	-0.071 (0.047)	-0.102 (0.080)
Pork, high PBM	0	N[0.075,0.025]	0	-0.125 (0.069)	-0.175 (0.117)
Poultry, low PBM	0	0	N[0.04,0.02]	-0.063 (0.040)	-0.128 (0.087)
Poultry, high PBM	0	0	N[0.075,0.025]	-0.110 (0.060)	-0.222 (0.121)
All meats, low PBM	N[0.04,0.02]	N[0.04,0.02]	N[0.04,0.02]	-0.132 (0.066)	-0.219 (0.115)
All meats, high PBM	N[0.075,0.025]	N[0.075,0.025]	N[0.075,0.025]	-0.231 (0.095)	-0.367 (0.153)

Table 10: Plant based meat adoption scenarios. Normally distributed shifts [*mean, st.dev.*]. Percentage corn and soybean price change in 2030 relative to base case without PBM.

output constant, estimates in Table 11 are a lower bound on the economic impact on corn and soybean producers. Results in Table 11 are economically significant in terms of local GDP.

Balistreri et al. [2019] quantified the impact on Iowa’s economy of the 2018 trade conflict between the US and China. The component of the decrease in crop prices between May and August, 2018, attributable to trade issues was on the order of 5% for corn and 13% for soybeans. This implies a \$1.1 billion drop in farm revenues, for a state GDP of \$190 billion. Hence, the trade war between the US and China would have had an effect both smaller and less permanent than a moderate adoption of PBM.

Naturally, this negative effect for farmers and commodity producers is mirrored by the benefit experienced by consumers through lower food costs. Commodity producing countries, however, are less likely to find offsetting flows. For instance, approximately half of

	GDP USD Bn	Corn Value USD Bn	Soybean Value USD Bn	Crop value change under low PBM in % of local GDP	Crop value change under high PBM in % of local GDP
Illinois	791	8.2	5.8	-0.30%	-0.52%
Iowa	173	8.9	4.70	-1.27%	-2.22%
Minnesota	374	4.7	3.10	-0.35%	-0.60%
Nebraska	117	6.4	1.90	-1.07%	-1.88%
Argentina	495	7.1	17.10	-0.95%	-1.64%

Table 11: Impact of the adoption of PBM for beef, pork and poultry on the market value of corn and soybean local output. Based of the level of output and market prices in 2019.

Argentina’s exports are soybeans, soybean meal, and corn. A permanent price change in Argentina’s main crops of the order estimated in this paper would have dramatic economic and political consequences.

5. Conclusion and extensions

In this paper we attempt to quantify the likely impact of the adoption of PBM on corn and soybean markets by year 2030. We assume that the development of PBM will be the main technological innovation on meat markets that is not fully incorporated today on OECD - FAO projections nor in current market prices. In the absence of historical data to perform an econometric exercise we adopt a simulation approach. We gather available estimates for the industrial production of beef, pork and poultry and for their reliance on corn and soybeans as feed. We obtain price elasticity measures from the literature. Model uncertainty is represented by an economically wide distribution for each of the parameters. We construct PBM adoption scenarios based on quantitative and qualitative information about consumer preferences, current growth trends, alternative food benchmarks, and investment industry analyses. We consider a low PBM adoption scenario where by 2030 a 2% to 6% of animal meat is replaced by PBM. By coupling this scenario with industry parameters and elasticities we find that the prices of corn and

soybeans could plausibly experience permanent declines in the 10%–17% and 16%–29% respectively, relative to prices in the absence of PBM. In 5%–10% adoption scenario, the prices of corn and soybeans could decrease by 18%–29% and 29%–47% respectively. Pork and poultry have a potentially much larger impact than beef on corn and soybean prices. The decrease in demand for corn and soybean would likely be replaced by a much smaller volume of crops used as inputs in PBM. Corn and soybean producers, at the farm and regional level, are likely to suffer from technological displacement. We estimate a 0.5%–2% local GDP decline in states in the US Midwest and in Argentina purely due lower market value of farming output. These estimates do not take into account probable declines in physical output and wider agricultural supply chain impacts.

Our study has several limitations. Production parameter estimates are taken from a literature that is very extensive and often focused on specific cases while the literature on price elasticities for corn and soybeans is very sparse. Results in this paper might depend, to some degree, on the selection of information sources. A linear model like ours misses nonlinear effects that are likely to emerge under a permanent demand shift as large as being considered in this paper. Our assumption that PBM will be the main disruptor in meat and grain markets by 2030 might not hold. In addition, the adoption of PBM at different speeds across meat types would lead to dynamical behavior that is not captured by a single horizon simulation. Spatial heterogeneity is also likely in reality. The decrease in grain demand associated with PBM should first impact regions with high production costs. Since these are spatially heterogeneous, the regional impact of PBM is also likely to be unequally distributed. All of these aspects are left for extensions of this paper and for future research.

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