Challenges Facing Agriculture: Evaluation of the Impact of AgTech, Recommendations, and Opportunity Identification in Food Waste Reduction

By

Guillaume Defrance de Tersant

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Submitted to the Integrated Design and Management Program and the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degrees of

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Signature of Author: Signature redacted

Integrated Design and Management Program
Department of Mechanical Engineering
May 7th, 2019

Certified by: Signature redacted

Douglas Hart, PhD
Professor of Mechanical Engineering
Thesis Supervisor

Accepted by: Signature redacted

Matthew S. Kressy
Executive Director, Integrated Design and Management Program

Accepted by: Signature redacted

Nicolas Hadjiconstantinou
Chairman, Committee on Graduate Students

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Abstract

Global food production faces severe challenges that will test the world's ability to mobilize technology, industry participants, and governments to develop a sustainable response. Feeding a growing population and accommodating for rapidly evolving diets calls for a significant expansion in production. Progress is needed to help produce more with less, limit the environmental impact of chemical inputs, and curb agricultural greenhouse gas emissions. The agricultural workforce is facing increasingly challenging economic conditions, a lackluster generation of new producers, and industrywide labor shortages that threaten the continuity of food production. Innovative systems are crucially needed to boost productivity, while protecting natural resources and sustaining a vital workforce. In the past decade, Agriculture has witnessed the rise of a novel proponent of such systems stemming from an unprecedented wave of investments, innovations, and entrepreneurial ventures, referred to as AgTech for the purpose of this work.

The aim of this work is initially to analyze the most pressing challenges faced by global food production, communicate on their magnitude, and highlight opportunities for innovation. In parallel, this work aims to increase awareness on the magnitude of food waste and loss, and present opportunities associated with food waste reduction and prevention. Then, this work will briefly define AgTech, present its benefits, and evaluate its impact on the food production industry. Based on this evaluation, limitations of AgTech will be presented, and industrywide recommendations to enhance its impact will be proposed. Finally, this work will propose a concept to reduce food waste in agricultural production.

Thesis Supervisor: Douglas Hart
Title: Professor of Mechanical Engineering

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This work would not have been possible without the amazing support of many exceptional individuals that I have met during my time at MIT. I will forever be grateful for the confidence initially placed in me by Matthew Kressy, and for his vision to create such an inspiring masters program. I would also like to thank Andy McInnis and Melissa Parillo for their unwavering support, warmth, and encouragements during the past three years. I am extremely grateful to Doug Hart for giving me the flexibility to work on a topic that I felt passionate about, for his mentorship, and for his courses that I will always remember very fondly. This work was born out of the willingness of numerous growers, advisors, and industry experts to lend me their time. I am thankful for their help, insights, and valuable advice. I also deeply enjoyed working with Helena Briones under the supervision of Professor Sang-Gook Kim on the later parts of this work.

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I have been blessed with an incredibly loving and supportive family – Hélène and Thibault; Marie, Louis, and their children; and Marie and Adrien. I am very grateful for their constant desire to see me thrive. This work is dedicated to my parents: Hélène and Thibault, for their unconditional kindness and generosity, and for giving me the freedom to be who I want to be as long as I am happy.

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Contents

List of Figures

List of Tables

1 Introduction

Global food production is facing severe challenges that will test the world's ability to mobilize technology, industry participants, and governments to develop a sustainable response. Feeding a growing population and accommodating for rapidly evolving diets calls for a significant expansion in agricultural production. The feasibility of such an expansion is uncertain, as experts point out that the benefits from the Green Revolution have already been reaped, and the chances of one happening again are limited. In parallel, the depletion of arable land and freshwater resources questions the sustainability of agricultural production. Progress is needed to help produce more with less, limit the environmental impact of chemical inputs, and curb agricultural greenhouse gas emissions. A key enabling factor in the development of a holistic response to these challenges will be the engagement of the agricultural workforce. However, it is facing increasingly challenging economic conditions, a lackluster generation of new producers, and industrywide labor shortages that threaten the continuity of food production.

Innovative systems are crucially needed to protect natural resources, while boosting productivity and sustaining a vital workforce. In the past decade, Agriculture has witnessed the rise of a novel proponent of such systems stemming from an unprecedented wave of investments, innovations and entrepreneurial ventures, referred to as AgTech for the purpose of this work. AgTech has expanded the boundaries of agricultural production, and has put forward models with significant benefits to farmers and consumers. These novel solutions must be adopted on a wide scale for these advances to come to fruition, and for demand to be sustainably met. However, several factors inherent to AgTech and the food industry have hindered their implementation. Changes are needed to ensure that there are sufficient incentives and support infrastructure for food producers to invest in these solutions. To achieve this, there must be an increased collaboration between all industry stakeholders, along with adequate governmental support. The future of food and agriculture faces uncertainties, but the cooperation of technologists, entrepreneurs, industry participants and governments will help overcome them.

1.1 Goals, motivation, and research methodology

The aim of this work is initially to analyze the most pressing challenges faced by food production, communicate on their magnitude, and highlight opportunities for innovation. In parallel, this work aims to increase awareness on the magnitude of food waste and loss, and present the opportunities associated with food waste reduction and prevention. Then, this work will briefly define AgTech, present its benefits and evaluate its impact on the food production industry. Based on this evaluation, one of the main goals of this thesis is to explain the limitations of AgTech, and propose industrywide recommendations to enhance its impact. Furthermore, this work will expose the gaps in food reduction innovation, and propose a concept to reduce food waste in agricultural production.

This work is primarily motivated by the multiple challenges faced by Agriculture, and the urgent necessity to develop innovative production systems. Challenges that have especially motivated the author are the increasingly challenging economic situation of farmers, and the overwhelming amount of food waste and loss in the food supply chain. Although Agriculture has a limited economic role, and only accounts for 3.5% of the world's Gross Domestic Product (GDP), it remains a foundational industry that employs 26% of the world's population, and occupies 37% of global land [1–3]. It has been a formidable engine of scientific progress in genetics and mechanization, and can still propose cutting-edge advances that can benefit most industries.

This work was initially born out of dozens of interviews with farmers, researchers, entrepreneurs and industry stakeholders conducted in the summer of 2018. To supplement these qualitative insights, a literature review was conducted, ranging from reports of international non-governmental organizations, to scientific research and news articles. Personal reflections and a secondary set of interviews helped build the recommendations proposed in the later parts of this thesis. The proposed concept to reduce food waste in agricultural production was developed through coursework taught by Professor Sang-Gook Kim at the Massachusetts Institute of Technology in the fall of 2018.

2 Challenges to Agriculture and the necessity for innovative solutions

Global food production is facing three severe challenges that will require unprecedented support, change and innovations to sustainably meet a growing and diversifying demand. First, there is an urgent need to find new sources of productivity growth to match the demand of a rising, increasingly urban population. Second, the heightening scarcity of natural resources and the looming threat of climate change require novel solutions to support the sustainability of the global food supply. Finally, plummeting profits and labor shortages in Agriculture put additional pressure on food security, and demand progress to sustain a crucially needed workforce. In this context, food waste and loss sheds light on the dysfunctions of the food supply chain and the chasms between producers, retailers and consumers. It constitutes a pool of opportunities to help meet demand, enhance agricultural sustainability and improve farming profits.

2.1 The urgent need for new sources of productivity growth

Although decelerating, population growth continually requires increases agricultural productivity. The FAO estimates that a 48.6% increase in global crop production is required to match the expected rise in demand by 2050 [4]. Even more so than before, yield increases will drive most of the needed production increment. Achieving them poses a formidable challenge in and of itself, as numerous experts argue that yield ceilings have been, or are being reached for major crops, which might trigger a surge in food prices in the coming years [5,6]. A tremendous wave of research and development spending is necessary to fuel progress in seeds and inputs, along with incentives and support structures to aid the adoption of new technologies on farmland. Concurrently, urbanization has triggered a global shift in diets that will require a rapid adaptation of food production systems.

2.1.1 Required yield increases to meet projected demand levels

The United Nations (UN) forecast that the world population will increase by 32.4% over the next 30 years, from 7.38 billion people in 2015 to 9.77 billion people in 2050 [7]. Developing nations will fuel 98% of the growth over this period, through an increment of 2.34 billion people, to reach 8.47 billion people by 2050. These forecasts mark a significant deceleration compared to the past 35 years. World population is projected to grow at an annual rate of 0.80% between 2015 and 2050; nearly half of what it was between 1980 and 2015 (1.45%).

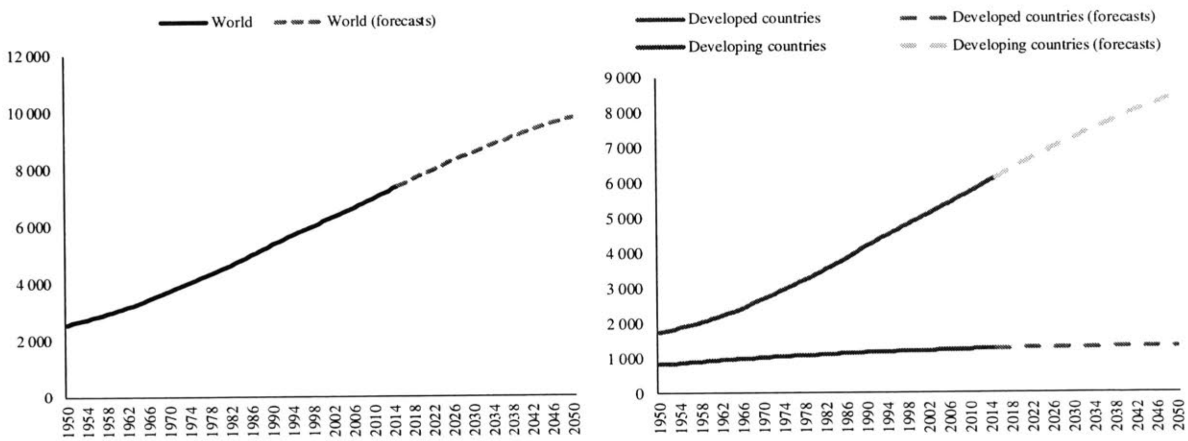

Figure 1. World population (millions): historical data and Medium Variant forecasts (1980 - 2050) [7].

Population growth, albeit slowing, demands a tremendous increase in global food production to supply an additional 2.39 billion mouths by 2050. In 2009, the United Nations Food and Agriculture Organization (FAO) had estimated that agricultural production needed to increase by nearly 60% between 2005 and 2050 to meet projected demand [4,8]. After a revision in 2017, the FAO currently estimates that agricultural production must increase by 48.6% compared to its 2013 levels, by 2050 [4]. This implies a 112.4% increase for Sub-Saharan Africa and South Asia, and a 34.2% increase for the rest of the world over this period [4]. Similarly, the World Resources Institute (WRI) estimates that global agricultural production needs to increase by 56% between 2010 and 2050 [9]. Their projections assume a faster shift in diets, and a notable 68% increase in the consumption of meat and milk over the period, which exceeds the rise in demand for these products between 1962 and 2010 [9].

Table 1. Increases in food production needed to match demand. AT2050 refers to 2009 estimates. Data from [4].

	2005/07 - 2050	2005/07 - 2012	2013-2050
World			
As projected in AT2050	59.6%	14.8%	44.8%
With updated population projections (UN, 2015)	63.4%	14.8%	48.6%
Sub-Saharan Africa and South Asia			
As projected in AT2050	124.9%	20.0%	104.9%
With updated population projections (UN, 2015)	132.4%	20.0%	112.4%
Rest of the world			
As projected in AT2050	44.9%	13.8%	31.2%
With updated population projections (UN, 2015)	47.9%	13.8%	34.2%

Even more so than in the past, yield increases will be the main drivers of crop production growth. Given the growing scarcity of arable land, yield growth is expected to drive 80% of global crop production growth between 2005 and 2050, as compared to 77% between 1961 and 2007 [10]. Arable land expansion will still be an important source of growth in agricultural output for countries of Latin America Sub-Saharan Africa (20% and 40% respectively), but its decline in regions like South Asia will put more pressure on cropping intensity and yield increases [10].

Table 2. Sources of growth in crop production (percent). From [10].

	Arable land expansion		Increases in cropping intensity		Yield increases	
	1961- 2007	2005/2007-2050	1961- 2007	2005/2007-2050	1961- 2007	2005/2007-2050
All developing countries	23	21	8	6	70	73
Sub-Saharan Africa	31	20	31	6	38	74
Near East/North Africa	17	0	22	20	62	80
Latin America and the Caribbean	40	40	7	7	53	53
South Asia	6	6	12	2	82	92
East Asia	28	0	-6	15	77	85
World	14	10	9	10	77	80
Developing countries with less than 20 percent of their potentially arable land in use in 2005/2007*		35		6		59
Developing countries with over 60 percent of their potentially arable land in use in 2005/2007**		4		6		90

** 24 countries with a gross land balance exceeding 80 percent of total suitable land in 2005/2007*
*** 19 countries with a gross land balance less than 40 percent of total suitable land in 2005/2007*

However, global food security will not just depend on yield increases. The fast growth of many developing nations puts even more pressure on already strained food systems, and requires novel solutions to facilitate access to food and support agriculture in impoverished regions [11]. Even if there is sufficient food supply in principle for nearly everyone to be well-fed, there were still 821 million undernourished people in 2017 [10,11]. That number has raised numerous concerns because of its renewed growth since 2014, as highlighted by Figure 2, thus writing off progress made between 2010 and 2014.

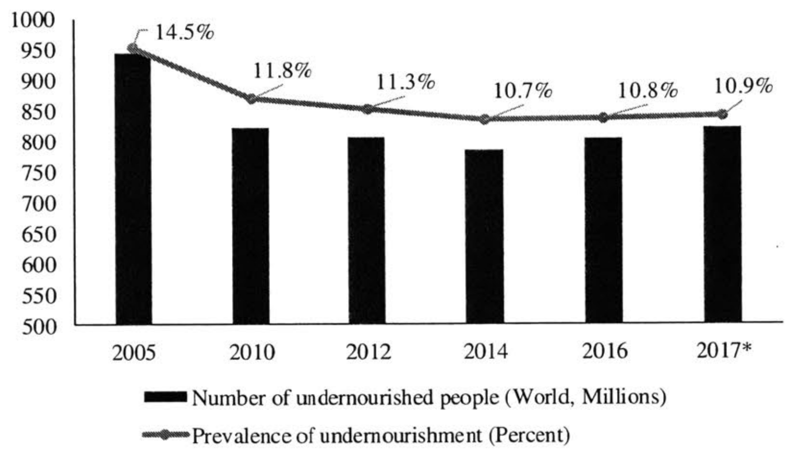

Figure 2. Undernourished people and prevalence of undernourishment [11].

This is partly due to a stark increase in undernourishment in arid countries, as evidenced by Table 3 below, itself a result of multiple reasons like the lack of appropriate financing for farmers, poverty, or instability in these regions.

Table 3. Number of undernourished people (millions) per region. From [11].

	2005	2010	2012	2014	2016	2017*
Africa	196	200.2	205.2	212.5	241.3	256.5
Asia	686.4	569.9	552.2	523.1	514.5	515.1
Latin America and the Caribbean	51.1	40.7	38.9	38.5	38.9	39.3
Oceania	1.8	1.9	2	2.3	2.6	2.8
North America and Europe	26.4	27	27.2	27.3	27.5	27.6
World	**945**	**820.5**	**805.7**	**783.7**	**804.2**	**820.8**

*: projected values

2.1.2 Concerns on the feasibility of necessary yield increases

Numerous experts question the feasibility of the yield increases needed to meet the production targets set by the FAO, as well as the potential for a continuation of growth in productivity [10]. The World Bank had alerted about this issue in 2008, after pointing out significant declines in crop yield growth rates in developing countries since the 1980s [5]. The deceleration was attributed to slowdowns in public research and development spending, the deterioration of soil and water quality, and the imbalanced use of nutrients [5]. This slowdown is taking place at a global level, as evidenced by the decrease of yield growth rates of cereal crops (averaged over 25 years) from c.2.5% per annum in the 1980s to c.1.5% in the 2010s [12].

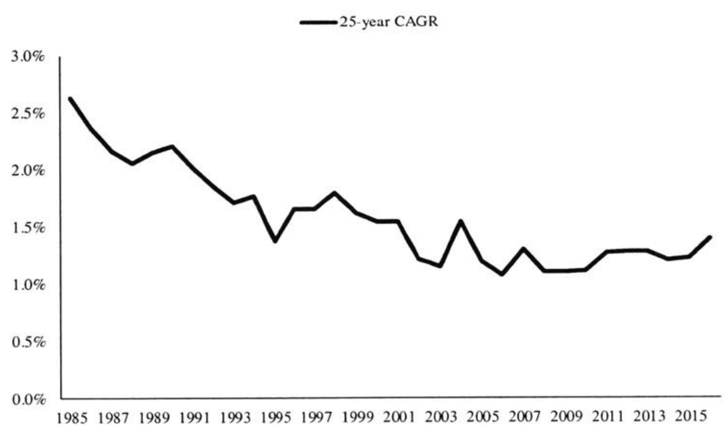

Figure 3. Global cereal yield growth rates, averaged over 25 year periods, derived from [12].

This observation also stands for developed countries with significant research and development spending. In the US, yield growth rates of corn and wheat (averaged over 25 years) have decreased from c.2.0% and c.1.2% in the 1980s to c.1.5% and c.0.8% in the 2010s, respectively [13].

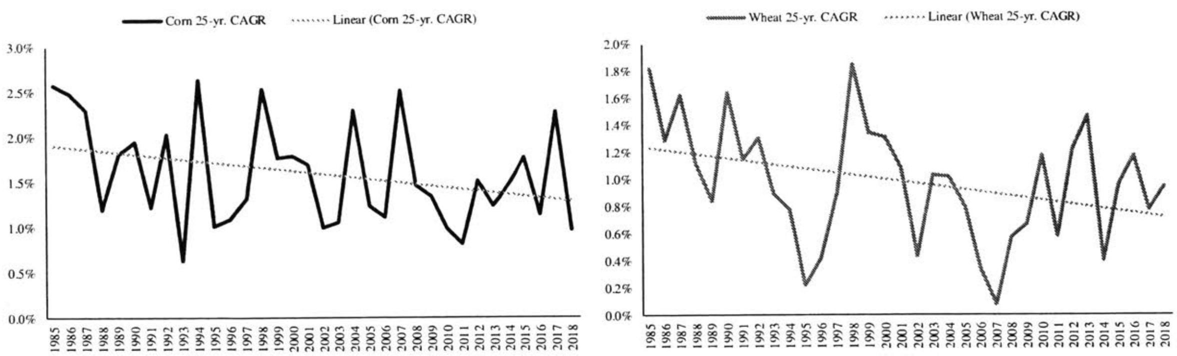

Figure 4. Yield growth rates for corn and wheat crops in the US, averaged over 25 years [13].

Among causes for concern, experts highlight that easy gains from the Green Revolution have already been reaped, and that the chances of one happening again are very limited [5,10]. Additionally, studies have discussed the possibility that yield growth for certain crops has plateaued, or even that yields have reached the maximum biophysical potential of crops [10,14]. A 2013 study led Grassini et al. argues that 21% of the global production of rice, wheat and maize have reached upper yield plateaus. 12% alone follow an increasing rate of productivity, while 10% are on a decreasing trend [14].

Table 4. Percentage of global crop production under different yield trajectories [14].

Crop species	% of global production	Increasing rate (%)	Constant rate (%)	Decreasing rate (%)	Upper yield plateaus (%)
Rice	84	19	23	9	33
Wheat	56	5	24	0	27
Maize	71	13	33	20	5
Total (rice, wheat, maize)	70	12	27	10	21

Historically, significant yield gains have been obtained by bridging the gap between average farm yields and experimental yields through the adoption of hybrid seeds, the widespread use of fertilizers and pesticides, and the expansion of irrigation equipment [14]. However, one concern today is that despite increases in research and development funding between 1981 and 2000 in countries like China and the US, rates of yield gains have remained linear, or even stagnated [14]. This situation highlights the need for an intensified growth in research and development spending to match production targets. Besides, it evidences the increasing complexity for farmers to maximize yield, who now have to optimize numerous facets of their operations simultaneously.

The gradual decline in arable land and the deceleration of crop productivity growth have fueled fears of significant food price increases in the future. In 2009, the International Food Policy Research Institute (IFPRI) estimated that world grain prices would increase by 30 to 50 percent by 2050, while meat prices would grow by an extra 20 to 30 percent as compared to 2007 levels, increments above historical trends [6]. Adverse environmental conditions induced by climate change could exacerbate these trends. Two climate change modelling scenarios, NCAR and CSIRO, point towards the possibility of additional prices increases compared to standard projections for maize: +51.9% and +55.1%, respectively [6]. Without adaptive action to curb climate change, along with significant innovations in resistant seed varieties, these scenarios could materialize and have devastating consequences on global food security.

Table 5. World prices of selected grains per scenario (USD per metric ton) [6].

	Baseline	NCAR-based scenario			CSIRO-based scenario	
	2000	2050 (no climate change)	2050 (with climate change)	% Change	2050 (with climate change)	% Change
Maize	95	155	235	51.9	240	55.1
Rice	190	307	421	36.8	406	32
Wheat	113	158	334	111.3	307	94.2

As mentioned above, tremendous innovations and increases in agricultural research and development will be needed to sustain yield growth, and curb food prices. This is especially true for developing countries, where the FAO identified a 50% gap in agricultural research and development funding (annual investments average $142 billion as opposed to a required $209 billion) in 2009 [8]. This gap is a result of a decline in both public and private agricultural research and development spending. Bridging it will require policies that support farmers and incentivize them to invest in new technologies, on top of funding increases. Similarly, the growth rate of public agricultural research and development has stalled in numerous regions: it went from 9.1% between 1960 and 1970 to 1.0% between 2000 and 2009 in high-income countries [4]. Specifically in the US, the share of public funding in agricultural research in development has gone from 50% between 1970 and 2008, to 20% between 2008 and 2013, underlining a sharp decline [15]. Currently, public agricultural research and development funding is supported for the most part by developing countries, and notably China, who drove 40% of global investments between 2000 and 2008 [16].

Table 6. Real growth of public agricultural research and development spending. From [4].

	1960-70	1970-80	1980-90	1990-00	2000-09
Low-income	6.0%	4.1%	3.1%	1.0%	2.3%
Lower middle-income	6.7%	3.3%	3.1%	3.2%	4.6%
Upper middle-income	4.3%	6.6%	2.8%	2.1%	6.2%
High-income	9.1%	3.3%	2.1%	1.6%	1.0%
China	-0.1%	7.8%	5.1%	3.9%	9.9%
India	9.8%	1.7%	5.6%	6.7%	5.2%
Sub-Saharan Africa	5.7%	2.7%	0.6%	-0.5%	4.0%
World	7.6%	4.1%	2.4%	1.9%	3.1%

Although there has been a surge in private funding for agricultural research and development, questions have been raised on whether this might compensate for the sharp slowdown in public investments. The latter is especially surprising since large bodies of literature have demonstrated that public agricultural research and development holds significant rates of return: between 20% and 60%, with a median rate of return of 40% [15]. These rates of return, in addition to the necessity of increasing production levels in the coming years call for a renewed and robust support of public agricultural research and development. While many believe that there are still significant exploitable yield gaps, there remains uncertainty on whether there will be enough public support to help develop new technologies, and assist farmers to invest in them [5].

2.1.3 Additional challenges associated to changing diets

Increasing productivity is not the only challenge to our global food system. Urbanization and rising incomes have sparked a shift in diets towards more resource-intensive foods that will require an adaptation of food production systems. The UN estimate that 68.4% of the population will live in cities by 2050, up from 51.7% in 2010 [17].

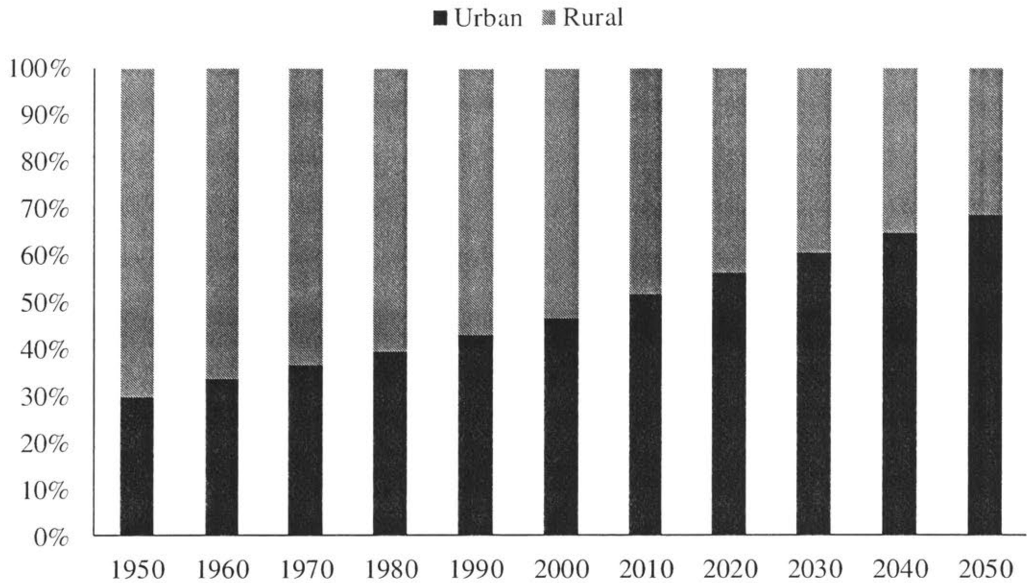

Figure 5. Global urbanization, historical figures and forecasts [17].

As opposed to rural populations, urban dwellers have a higher calorie intake, and consume more animal protein, fats, sugar, and processed foods [18]. As a result, there has been a global increase in per capita food consumption, which is expected to continue as urbanization increases [10]. Globally, the calorie intake per person is poised to increase by 7.3% and 9.5% between 2015 and 2050 for the world and developing countries, respectively [10].

Table 7. Per capita food consumption (kcal/person/day) [10].

	2005/ 2007	2015	2030	2050
World	**2772**	**2860**	**2960**	**3070**
Developing countries	**2619**	**2740**	**2860**	**3000**
Sub-Saharan Africa	2238	2360	2530	2740
Near East / North Africa	3007	3070	3130	3200
Latin America and the Caribbean	2898	2990	3090	3200
South Asia	2293	2420	2590	2820
East Asia	2850	3000	3130	3220
Developed countries	**3360**	**3390**	**3430**	**3490**

Similarly, the FAO projects a sharp increase in the consumption of meat and dairy between 2005 and 2050: +26% and +19% at the world level respectively, and +50% and +46% in developing countries [10].

Table 8 below provides additional details in the evolution of the diet composition at the world level, as well as for developing countries.

Table 8. Diet composition in kcal/person/day [10].

	2005/2007	2030	2050
World			
Cereals, food	158	160	160
Cereals, all uses	*314*	*329*	*330*
Roots and tubers	68	73	77
Sugar and sugar crops (raw sugar eq.)	22	24	25
Pulses, dry	6.1	6.6	7
Vegetable oils, oilseeds and products (oil eq.)	12	14	16
Meat (carcass weight)	39	45	49
Milk and dairy, excl. butter (fresh milk eq.)	83	92	99
Other food (kcal/person/day)	294	313	325
Total food (kcal/person/day)	**2 772**	**2 960**	**3 070**
Developing countries			
Cereals, food	155	159	158
Cereals, all uses	*242*	*254*	*262*
Roots and tubers	66	73	78
Sugar and sugar crops (raw sugar eq.)	19	22	24
Pulses, dry	7	7.4	7.7
Vegetable oils, oilseeds and products (oil eq.)	10.1	13.1	15.4
Meat (carcass weight)	28	36	42
Milk and dairy, excl. butter (fresh milk eq.)	52	66	76
Other food (kcal/person/day)	253	279	293
Total food (kcal/person/day)	**2 619**	**2 860**	**3 000**

This creates an additional challenge for our food system, since these foods are the most resource-intensive, and increase the pressure on an already strained environment. Fruit and vegetables, dairy, and animal protein are among the most demanding in energy use and blue water footprint, while their production leads to higher than average GHG emissions [19].

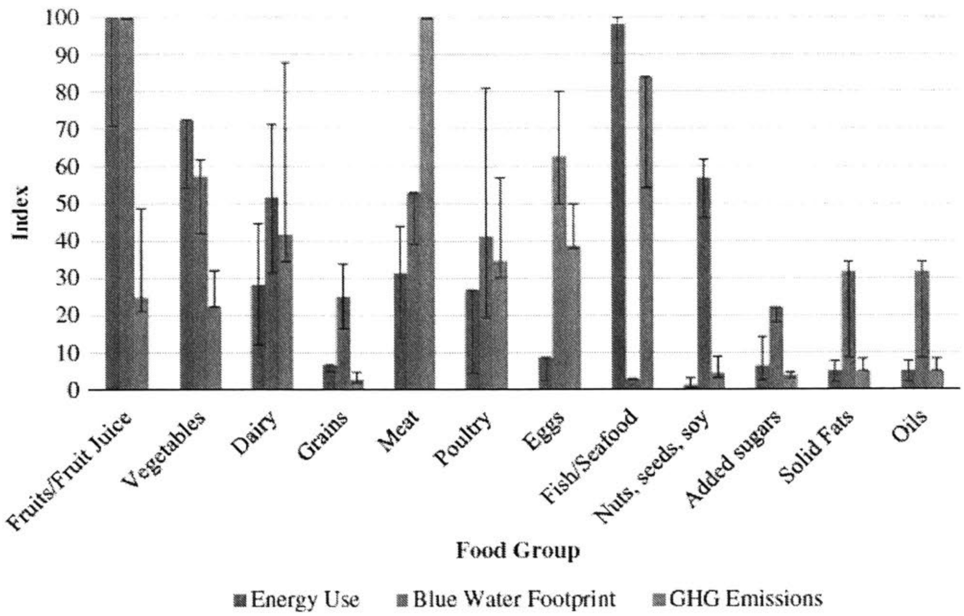

Figure 6. Energy use, blue water footprint, and greenhouse gas emissions per food (index). Figure from [19].

Overall, urbanization magnifies the pressure on food production to meet the demand of large, concentrated populations. Shifting diets require a rapid adaptation, along with novel solutions to help sustainably meet demand.

2.2 The shortage of natural resources and the need for increased sustainability

Numerous experts question the sustainability of the food production system, because of its heavy reliance on land and irrigation expansion, significant amounts of inputs, and the transportation of products over long distances [10]. The finiteness of available arable land and the scarcity of freshwater resources require novel solutions to help produce more with less. Similarly, progress is needed to limit the impact of agricultural inputs on the environment, and curb agricultural greenhouse gas (GHG) emissions. Finally, the potential impact of climate change on yields and crop stresses will demand advances in resistant seed research, if future food demand is to be met. Overall, significant research and innovation efforts will be needed to surpass these challenges, as many experts call for a shift towards *sustainable intensification* (i.e. the increase of food production from existing farmland without negative environmental impact) [10].

2.2.1 The finiteness of land and freshwater resources

The FAO estimates that arable land in use has grown at an annual rate of 0.28% between 1961 and 2007 [10]. Paralleled with a faster population growth, this had led to a steady decline in arable land per person, a measure often used to illustrate the need for productivity gains when compared to growing food demand.

Table 9. Total arable land in use (millions ha): historical data and projections [10].

	Arable land in use		Annual growth	
	2005/ 2007	2050	1961- 2007	2005/ 2007 - 2050
World	**1 592**	**1 661**	**0.28**	**0.1**
Developed countries	624	586	-0.17	-0.14
Developing countries	968	1 075	0.65	0.24
idem excl. China and India	668	775	0.74	0.34
Sub-Saharan Africa	240	291	0.83	0.44
Latin America	202	251	0.98	0.49
Near East / North Africa	84	84	0.31	0
South Asia	206	213	0.14	0.08
East Asia	236	236	0.93	0

Globally, arable land per person has declined by 54%, from 0.42 ha/person in 1961 to 0.19 ha/person in 2016. In least developed countries, it has decreased by 61%, from 0.46 ha/person to 0.18 ha/person [20].

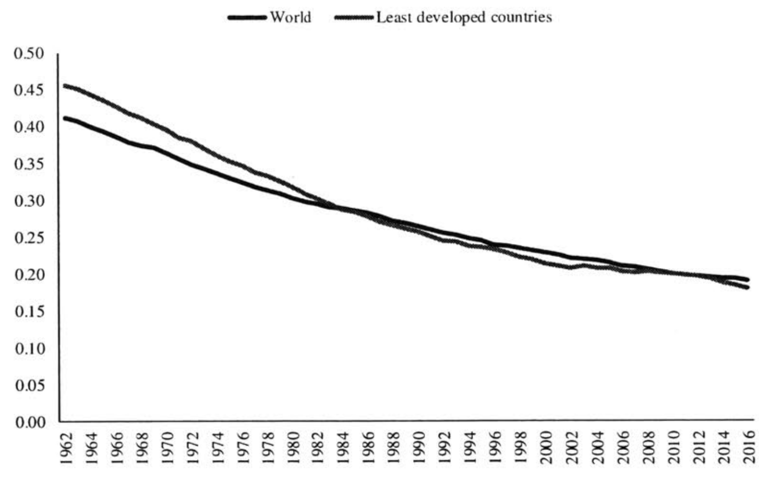

Figure 7. Arable land per capita (ha/person) [20].

Experts project this trend to continue, as arable land in use will only grow at an annual rate of 0.1% until 2050, being the main reason for the necessary level of yield increases mentioned in 2.1.1 [10]. This situation is even more concerning as there is an intensifying competition for land use between agriculture and biofuel production. The FAO estimates that by 2050, 6.1% of cereal crops and 24.3% of sugar crops will be used for biofuels, up from 3.2% and 15.1% in 2005/2007, respectively [10]. Should this trend continue, it might disrupt food production systems, possibly to the benefit of producers, but to the detriment of low-income consumers. According to the WRI, goals set by developed countries in terms of biofuel production could, if met, increase the existing food gap toward 2050. Multiple governments have announced that they aim to increase the share of biofuel used for transportation fuel by 400% in the coming years [9]. Such an increase would cover only 2% of transportation fuel needs in 2050, but it would increase the food gap from 56% to 78%, according to the WRI [9].

Table 10. World use of crops for biofuels (percent) [10].

	2005/2007	2030	2050
Cereals	3.2	6.7	6.1
Vegetable oils	4.8	12.6	10.3
Sugar	15.1	27.4	24.3
Cassava	0.4	2.3	1.8

Soil erosion stemming from agriculture is an additional threat to the availability of land for food production. A third of the planet's land has already been severely degraded, and 24 billion tons of arable land are eroded each year because of practices like heavy tilling [21–23]. This has two highly detrimental consequences: a significant economic burden to recover from nutrient losses, valued at $33-60 billion per year, and a massive carbon debt due to lowered carbon sequestration in the soil, estimated at 133 billion tons [22,23]. Soil erosion also causes productivity losses, as well as eutrophication of waterways and reservoirs [24]. Thus, increasing yields alone will not be enough to limit environmental damage caused by unsustainable practices. Instead, innovative solutions, such as controlled traffic, variable depth tillage, and conservation practices like no-till farming will need to be widely adopted.

Another crucial question is whether there will be enough water resources to meet the needs of food producers and other users alike. Agriculture accounts for nearly 70% of freshwater withdrawals in the world, and is deemed to be the main responsible behind the scarcity of freshwater in certain regions [10]. Because of the growing needs of agriculture, industry, and cities over time, the FAO estimates that 40% of the world's rural population lives in areas that are classified as water scarce [4]. This increasing scarcity calls for novel solutions to enhance water use efficiency, and thus reduce the pressure of irrigation on these regions' freshwater resources. In 2012, the FAO pointed out that the world average for water use efficiency (i.e the ratio between crop water requirements and irrigation water withdrawal) was at 50%, and projected to stagnate towards 51% in 2050 [10]. This stems from losses of water during transport and distribution, as well as irrigation practices such as field flooding, plant protection, and weed control, which require significant amounts of water. As a result, there is significant pressure on renewable water resources (measured as the ratio between irrigation water withdrawal and renewable water resources), up to 52% in North Africa, or 40% in South Asia. These figures highlight the need for novel irrigation solutions that can further optimize agricultural water consumption; and the need for increased support to help farmers adopt technologies such as drip irrigation.

Table 11. Water use efficiency and pressure on water resources due to irrigation. Adapted from [10].

	Water use efficiency ratio		Pressure on water resources	
	2005/2007	2050	2005/2007	2050
World	**50%**	**51%**	**7%**	**7%**
Developed countries	41%	42%	4%	4%
Developing countries	52%	53%	8%	9%
Sub-Saharan Africa	25%	30%	3%	4%
Latin America	42%	42%	1%	2%
Near East/North Africa	56%	65%	52%	54%
South Asia	58%	58%	40%	39%
East Asia	49%	50%	8%	9%

2.2.2 The increasing environmental impact of agricultural inputs

Although the wide adoption of chemical inputs such as fertilizers and pesticides has brought about significant productivity improvements, it has also triggered detrimental environmental consequences. Globally, around 115 million tons of mineral nitrogen fertilizers are applied to croplands each year, 20% of which accumulate in the soils, and 35% enter the oceans [25]. This has led to an estimated 24% of the global land area under irrigation to be affected by salinization [25]. Nitrate is considered the most common chemical contaminant in the world's aquifers, and has been reported as a major issue in Europe, the United States, and South and East Asia [26]. In many OECD countries, nitrate levels in groundwater exceed prescribed drinking limits in 10-15% of cases, a number that goes up to 33% for Europe's groundwater bodies [26]. In the US, the EPA deems nutrient pollution as *one of America's most widespread, costly and challenging environmental problems, caused by excess nitrogen and phosphorus in the air and water* [27]. Nutrient pollution also favors the generation of algal blooms, thus hurting industries and sectors that depend on clean water [28]. In the US, federal, state and local governments spend billions of dollar per year to prevent the effects of nutrient pollution [28]. If no novel substitutes to fertilizers or solutions to mitigate nutrient runoff are developed, this situation will be aggravated. Increasing amounts of fertilizer are expected to be used, because of its growing adoption on farmland, and the need to use it in larger quantities to maximize yield [10]. Globally, fertilizer consumption is expected to grow by 45%, from 132 kg/ha in 2005/2007 to 191 kg/ha in 2050 [10].

Table 12. Fertilizer consumption per harvested hectare. From [10].

	kg/ha	
	2005/ 2007	2050
Sub-Saharan Africa	8	27
Latin America	122	250
Near East / North Afric:	113	170
South Asia	121	268
East Asia	210	256
Developing countries	127	200
Developed countries	144	166
World	**132**	**191**

Similarly, pesticides have been recently put under the spotlight because of their increasing environmental cost, and potentially detrimental consequences to human health. Worldwide, 4.6 million tons of chemical pesticides are sprayed in the environment each year [25]. This intense spraying is estimated to have an annual $8 billion economic impact on non-target species (including humans) in developing countries [25]. Farmers rely heavily on these chemicals for crucial operations, such as weeding, leading to an estimated 200 million pounds of herbicides sprayed annually by US farmers on their fields [29]. However, this intense use has led FDA chemists to find trace amounts of it in numerous common foods, such as wheat crackers, granola cereal and corn meals, according to a recent inquiry [29]. Roundup, one of the most widely used weedkillers was recently alleged to be a substantial factor in causing cancer [30]. Two plaintiffs (Edwin Hardeman and Dewayne Johnson) were awarded significant damages in lawsuits against its manufacturer [30]. There is more: repeated spraying of herbicide has led to the emergence of 255 herbicide resistant weed species over time, thus evidencing the unsustainability of these chemicals to durably treat weeds [31]. These challenges make a strong case for the development of novel substitutes to agricultural chemicals, and innovative solutions to mitigate our reliance on them, or increase their efficacy.

There is an urgent need to curb agricultural greenhouse gas (GHG) emissions. Agriculture already constitutes 56% of non-CO2 emissions, and the global food systems account for 19-29% of total GHG emissions, according to CGIAR research [32]. Due to growing food production, the WRI projects emissions caused by agricultural production will increase by 33% between 2010 and 2050, from 6.8 Gt to 9.0 Gt of CO2 [9]. Put together with emissions stemming from agricultural land expansion and drained peatlands, this number would go up to 15 Gt by 2050 [9]. This will represent close to 70% of the total allowable emissions for all sectors by 2050, if we are to hold global warming below 2 degrees Celsius [9].

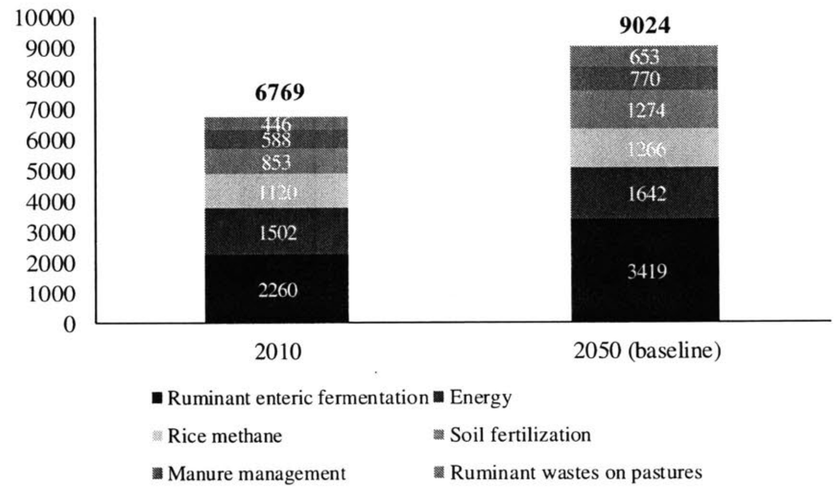

Figure 8. Baseline forecasts of agricultural GHG emissions (million tons of CO2). From [9].

Although the contribution of agriculture to global GDP is likely to be below 2% by then, it alone would fill 70% of the global emissions budget in 2050 [9]. These projections are especially concerning since, as mentioned in 2.1.3, diets are shifting towards the larger consumption of foods that lead to higher emissions.

2.2.3 The looming threat of climate change on Agriculture

The potential increase on food prices, briefly mentioned in 2.1.2, is partly attributed to the negative effects of climate change on agricultural production. First, multiple modelling efforts and climate change scenarios predict that rising temperatures could severely affect crop yields [6,33]. For instance, the CSIRO climate change scenario projects that crop yields of rice and wheat could decrease by up to 14.4% and 28.3% respectively, in irrigated areas of developing countries [6].

Table 13. Simulated impact on yield in 2050 from three climate change scenarios (percent change). From [6].

	CSIRO		NCAR		MIROC	
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
Maize						
Developing regions	-2	0.2	-2.8	-2.9	-5.3	-3.5
Developed regions	-1.2	0.6	-8.7	-5.7	-12.3	-29.9
Rice						
Developing regions	-14.4	-1.3	-18.5	-1.4	-11.9	0.1
Developed regions	-3.5	17.3	-5.5	10.3	-13.3	-12.8
Wheat						
Developing regions	-28.3	-1.4	-34.3	-1.1	-13.4	-10.4
Developed regions	-5.7	3.1	-4.9	2.4	-11.6	-9

Similarly, simulations conducted by the National Climate Assessment (NCA) have shown that crop yields of cotton and sunflower could decrease by over 20% in the next 80 years because of global warming [33]. Overall, the NCA forebodes increasing stresses on agricultural production due to extreme heat, drought, and heavy downpours [33]. Weeds, insects and diseases already have a negative impact on crop and livestock production, which could be magnified by climate change [33]. In parallel, the degradation of arable soil and freshwater is expected to continue at an accelerating rate, because of extremes in precipitation [33]. Finally, these effects could also cascade into other layers of the food systems, with climate change reportedly having a negative impact on protein and mineral concentration in foods [4]. Unless novel conservation methods are implemented, or increased innovation is developed, it is unlikely that Agriculture can endure climate change unaffected [33].

2.3 The shortage of producers and the urgent need to improve farming income

A crucial, yet often overlooked question is whether there will be enough farmers to ensure sufficient levels of food supply by 2050. In the US, the average of farmers have increased significantly in recent decades, surging to 58.3 years old in 2012, being perhaps the starkest evidence of the lack of new farmers coming into agriculture [34]. Because of increasingly expensive inputs and unstable prices, farming profits have plummeted, often leaving farmers with negative returns for major crops. Across the farming sector, there has been an intensified shortage of farm labor, sometimes threatening the continuity of their operations. Overall, there is an urgent need to support farmers and enhance their profit levels to sustain this vital workforce.

2.3.1 The shrinking generation of new farmers

It has become increasingly challenging for the farming industry to generate new producers, and it is perhaps best exemplified by the rapid aging of American farmers. In the US, the average age of farmers has been on the rise for the past 40 years, and has surged from 50.3 years in 1978 to 58.3 years in 2012 [34]. Farmers over 55 years old now represent over 60% of all farmers in the US [34]. This aging workforce represents a looming peril for the industry, since it is still unclear whether a new generation of farmers will emerge after it retires in the coming years.

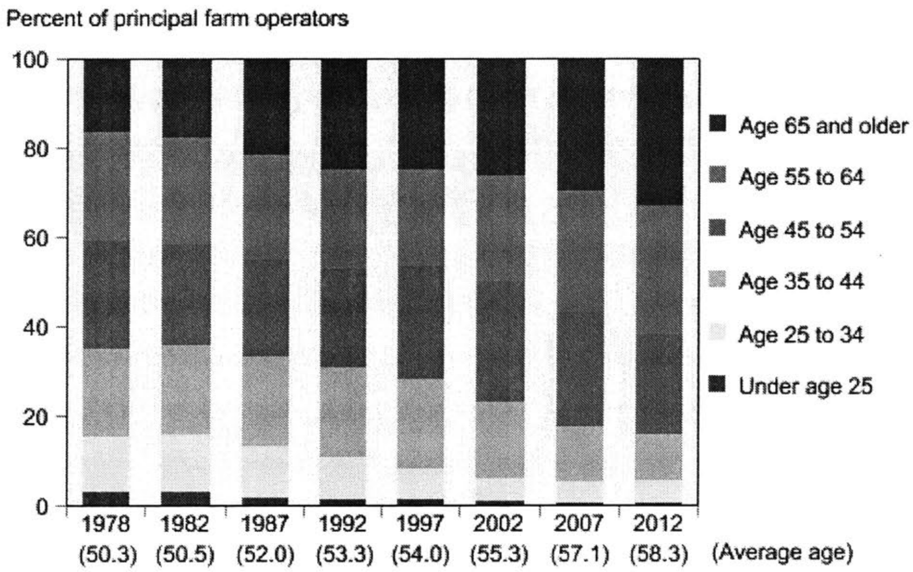

Figure 9. Age distribution of principal farm operators (1978-2012). Figure taken from [34].

Overall, the agricultural workforce is facing a lack of new farmers. Because of surging prices, buying land has become one of the biggest hurdles to the arrival of new farmers in the industry. *Land access is the top challenge young farmers face*, said Holly Rippon-Butler, the Land Access Program Director for the National Young Farmers Coalition (NYFC) in 2018 [35]. Land prices in the US have surged by 1600% since the farm crisis of the 1980s, making the upfront cost to own land prohibitive for many young farmers [35]. Renting farmland could be an alternative, but it is often too heavy a financial burden, leading novice farmers to struggle if they opt for it [35]. The United States Department of Agriculture (USDA) estimates that non-operators currently own

30% of farmland, and that this number is on the rise [36]. The latter perceive farmland as a financial investment, which often makes production economics even more challenging than they already are. This situation is likely to get worse, as an estimated 100 million acres of US farmland will change owners in the next few years, which should not make land or rent more affordable [36].

This challenging situation and historical reasons have led to a higher concentration of farms under family-owned businesses, one of the last mechanisms through which new farmers come into the industry. In 2017, 98% of US farms were family farms according to the USDA, and they accounted for 87% of food production [37].

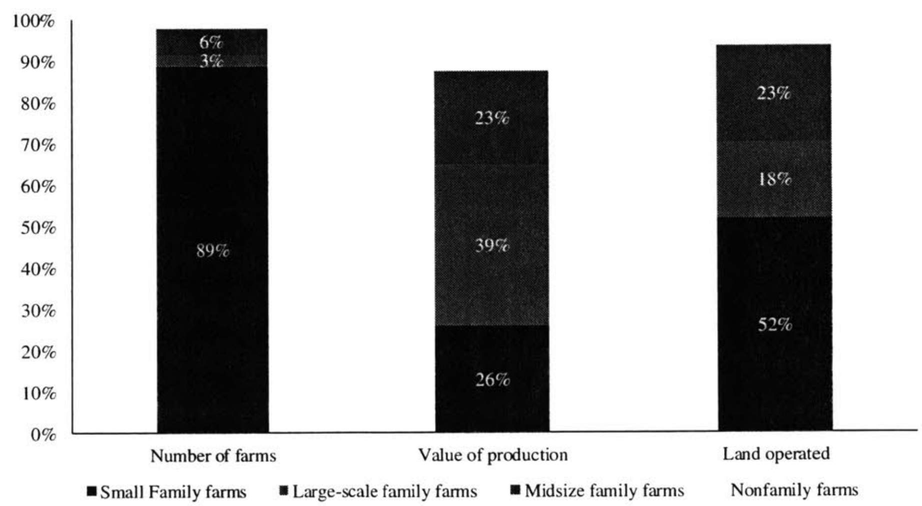

Figure 10. Distribution of farms, production value and land operated by farm type, 2017 [37].

Except for high-value crops where they account for 25% of the value of production, non-family farms are responsible for an increasingly lower value of production for numerous crops, such as grains, cotton and dairy (see Figure 11 below for more detail). Currently, family farms seem to serve as one of the last mechanisms to generate new farmers in the sector. Children often inherit land and take over their parents' operations, but this trend has also been decreasing, because of lowering economic incentives, tightening profit margins and higher financial risks.

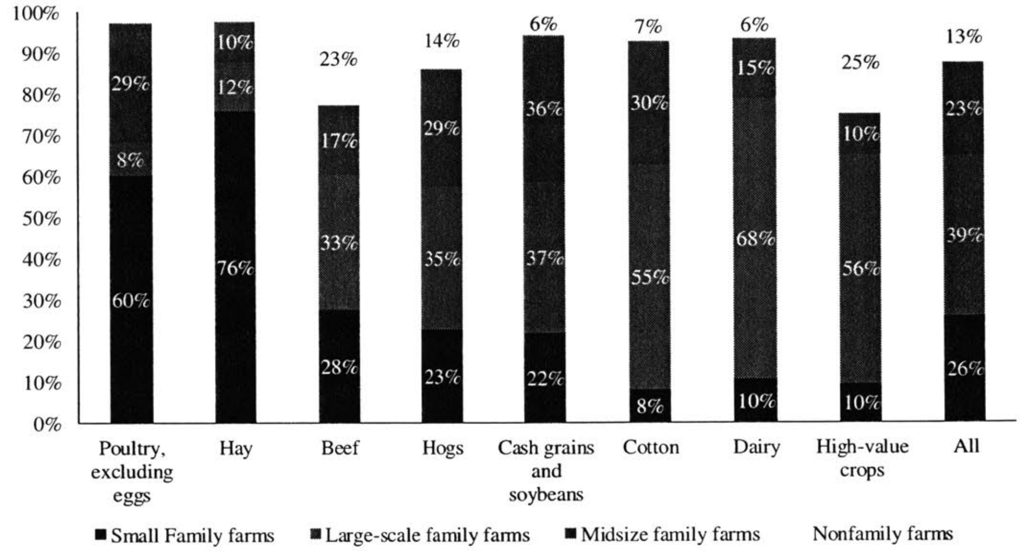

Figure 11. Value of production for selected commodities, by farm type, 2017 [37].

2.3.2 The lack of economic incentives to become a farmer

Besides buying farmland, one of the major obstacles that hinders the generation of new producers are the lowered economic incentives to become one. The combination of unstable, declining commodity prices, with the surge in input costs in the past decades has had a drastic impact on farm profit levels. Farmers are especially vulnerable to fluctuations in commodity prices, which have been facing a sharp decline despite an uptick in the early 2010s. Corn prices have decreased by 51% between 2012 and 2017, from 6.89 $/bu to 3.36 $/bu, while soybean prices have decreased by 35% over the period, from 14.4 $/bu to 9.3 $/bu [13].

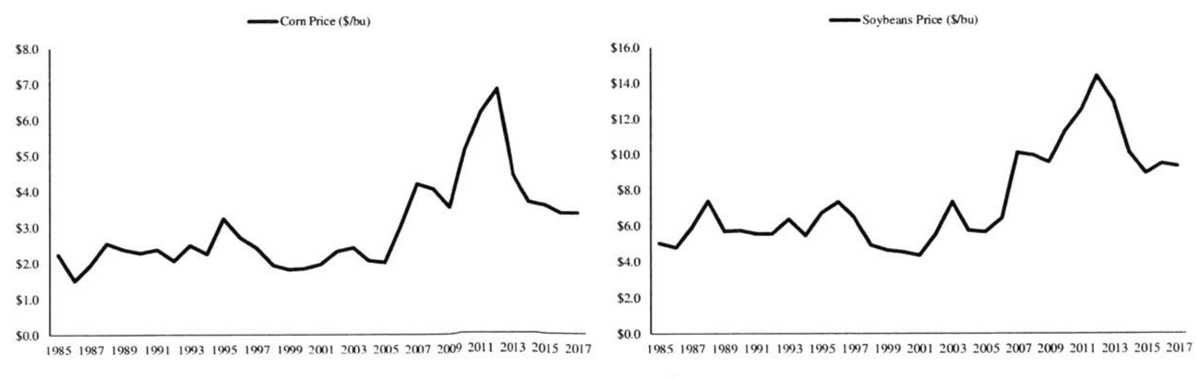

Figure 12. Corn and soybean prices ($/bushel) [13].

In parallel, input costs have risen to the point where they exceed the price of the output created by farmers. Farmers now have to rely increasingly on off-farm income to make ends meet, and net returns for major crops such as corn can sometimes be negative.

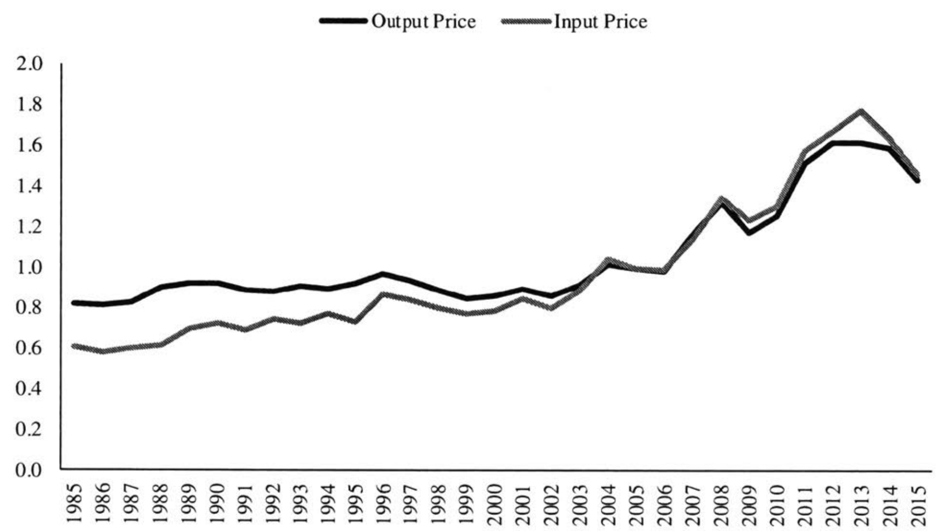

Figure 13. Input and output price indices, as computed by the USDA [13].

As a result of decreasing commodity prices and rising input costs, farmers' profit levels have plummeted in the past 50 years. Despite a strong growth in gross cash income stemming from crop production growth (made of crop receipts, animals and product receipts, machine hire, government payments…etc.), cash expenses (interest, labor expenses, input costs, rent…etc.) have risen to the point where net cash income (difference between gross cash income and cash expenses) has not been able to keep up.

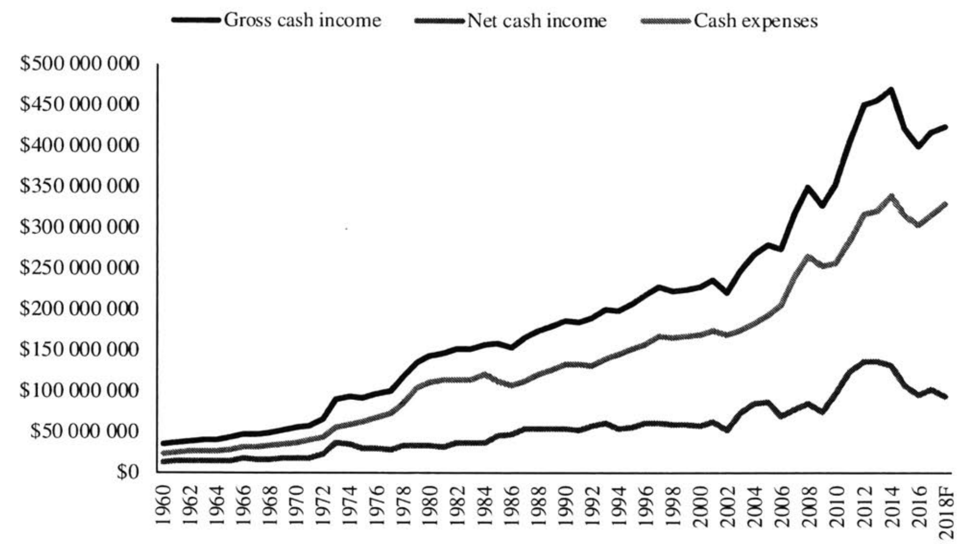

Figure 14. US farming gross cash income, net cash income and cash expenses [13].

Consequently, net farm income margins have steadily decreased in the past decades, from around 35% in the 1960s to around 20% in the 2010s [13].

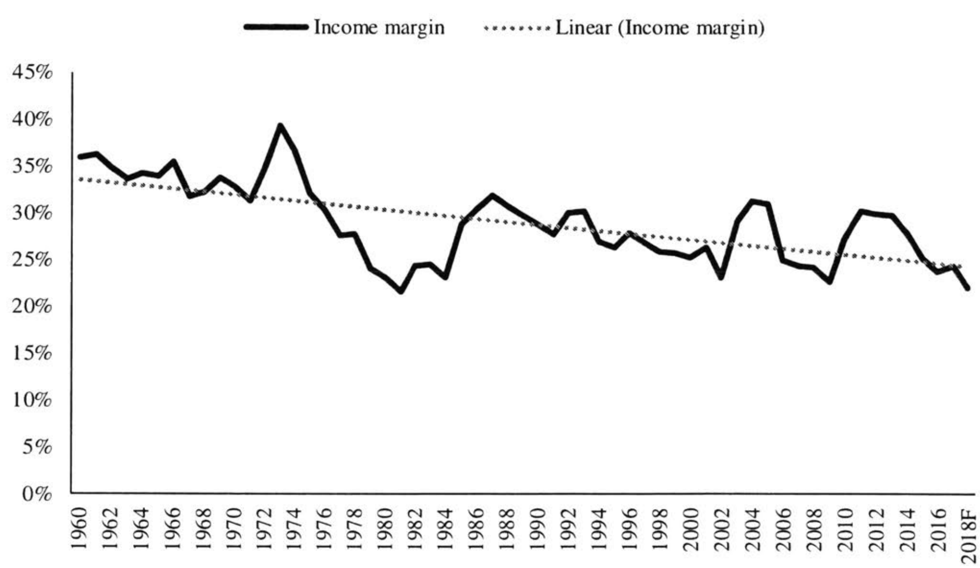

Figure 15. US net cash farm income margin. Derived from [13].

Based on a recent FINBIN (an aggregator of US farm business management data) analysis for the years 2014-2016 on 850 crop farms, the average return for cash rented corn was negative $51.82

per acre per year, despite above average yields for these years [38]. The FINBIN analysis suggests that such tight profits (or often losses) are likely to continue for coming years [38]. These figures point out the absence of sufficient economic incentives to become a farmer nowadays. While this is primarily supported by US data, this finding also stands true for other regions. Tremendous innovations and progress will be needed to enhance farming profits and sustain a workforce that is vital for food security. Government support is not a sustainable solution, and will not be enough to prevent this situation from worsening.

2.3.3 The increasing labor shortage across the farming sector

Another threat has been jeopardizing the continuity of farming operations: an industrywide shortage of farm labor, especially in developed countries like the US. This has led to a rise in labor expenses, and the disruption of operations to the point where significant portions of crops are left unattended. This situation is perhaps best represented by quotes of farmers, who have complained about labor shortages for decades. *There's not enough guys, and everybody is fighting for everybody else's guys*, said a California grape producer in 2017 [39]. Similarly, the president of the Florida Farm Bureau expressed in 2017: *an insufficient farm labor force continues to plague many agricultural commodity groups ranging from dairy to specialty crops* [39]. In the US, this situation has been magnified by recent immigration efforts to curb unauthorized farm work. *The threat of deportation and the potential loss of our workforce has been very terrifying for all of [our] businesses here*, stated the representative of a large feed yard in Kansas in 2017 [39]. Should these efforts intensify, *certain parts of this industry and this region will not exist* voiced a Californian producer of peaches, plums and grapes in 2017 [39]. To maintain their workforce, producers have had to raise agricultural wages, often to the point where they could not make a profit. Between 2014 and 2017, the average hourly wage for nonsupervisory hired farmworkers increased by 7%, up to $12.47 [39]. Increases in farm wages are not new, but have been among the fastest observed since 1989 [39]. These rates of increases have surpassed the wage growth in other industries by 11% over the past decade [39]. As compared to farm work, nonfarm wages increased by only 3% between 2014 and 2017 [39].
The case of California is the most representative of these heightening difficulties. According to UC Davis cost studies, the hourly cost of field labor has increased by 35% between 2010 and 2015, while the hourly cost of machine labor has increased by 55% over the period (see Table 14

below for more detail) [40]. Among the factors behind these trends, UC Davis quotes the adoption of a recent overtime law, the reduction of Mexico – US migration since the recession, and immigration policies [40].

Table 14. Farm labor wages in California ($/hour) [40].

	2010	2015	% change
Field labor (base wage)	8.5	11.5	35%
Field labor and benefits	11.4	16.1	41%
Machine labor (base wage)	10	15.5	55%
Machine labor and benefits	13.4	21.7	62%

This labor shortage has been a major disruption for farming operations. It was estimated by the Natural Resources Defense Council (NRDC) in 2012 that 20% of fruits and vegetables grown in the US do not leave the farm [41]. This is either because of high labor expenses that crop revenue do not make up for, or because farmers cannot find enough workers [41,42]. Novel solutions are needed to help farmers overcome this crisis. Several farming organizations have called for the development of automated solutions for labor-intensive activities, such as weeding or harvesting. Overall, innovations are needed to ensure the sustainability of farming operations and improve their financial situation.

2.4 Opportunities in food waste reduction and prevention

The need for progress and innovation is increasingly apparent to help solve pressing challenges in Agriculture. As many organizations call for productivity increases to help meet the needs of a growing population, there is also a growing incentive to mitigate food loss and waste. Currently, 30-40% of our food is wasted or lost throughout the food supply chain [43,44]. Finding long-lasting remedies to prevent and reduce this number would considerably help meet demand growth, limit the environmental impact of agriculture, and improve farming profitability. In short, this would support the transition of agriculture towards sustainable intensification. However, there is no silver bullet to solve food loss and waste. It will require tremendous innovations, policies and collaboration at all stages of the food value chain.

2.4.1 Overview of food loss and waste

It is estimated that about 30-40% of produced food is wasted or lost throughout the food supply chain [41,44]. According to the FAO, food loss is generally caused by defects of the food production and supply system, or its institutional or policy framework [44]. Food waste refers to the removal of food from the supply chain, because it is deemed improper for human consumption [44]. The former is generally attributed to the lack of proper storage facilities, cold chain, infrastructure or efficient marketing systems; while spoilage, poor stock management or neglect cause the latter [44]. 30-40% of total produced food represents an annual waste of 1.6 billion tons, or about 10 times the amount of matter that constitutes Manhattan [43]. This massive waste comes with an equally significant economic burden, with the cost of food waste being estimated at $1.2 trillion each year [43]. Fruits and vegetables are the most wasted foods (46%), and represent 40% of the quantity of food waste, or 644 million tons of produce [43]. Table 15 below breaks down food loss and waste per food category.

Table 15. Food loss and waste per category [43].

	Fish and seafood	Oilseeds and pulses	Meat	Milk and eggs	Roots and tubers	Cereals	Fruits and vegetables
Percentage lost or wasted	35%	22%	21%	17%	46%	29%	46%
Amount lost or wasted in tons	22M	50M	74M	143M	275M	347M	644M

Food loss and waste happen at every stage of the food supply chain. Even though waste happening at the consumption level is the most costly ($500 billion per year), the highest quantities of waste happen during production (500 million tons per year) [43].

Table 16. Food loss and waste at each stage of the food value chain [43].

	Production	Handling and storage	Processing and packaging	Distribution and retail	Consumption
Lost or wasted food per year (in tons)	500M	350M	160M	200M	340M
Lost or wasted food per year (in value)	$230B	$120B	$130B	$210B	$500B

Food loss and waste tends to be more significant during consumption in developed countries (17% of fruits and vegetables are lost during consumption in the US, as compared to 3% in Sub-

Saharan Africa) [44]. It occurs in larger quantities during processing in developing countries, where cold chains and infrastructure are sometimes insufficient to handle food (18% of fruits and vegetables are lost or wasted during processing in South and Southeast Asia, as opposed to only 1% in Europe) [44]. Figure 16. Percentage of food loss and waste at each phase of the food supply chain for fruits and vegetables *[44]*.Figure 16 below has more detail on these geographic differences.

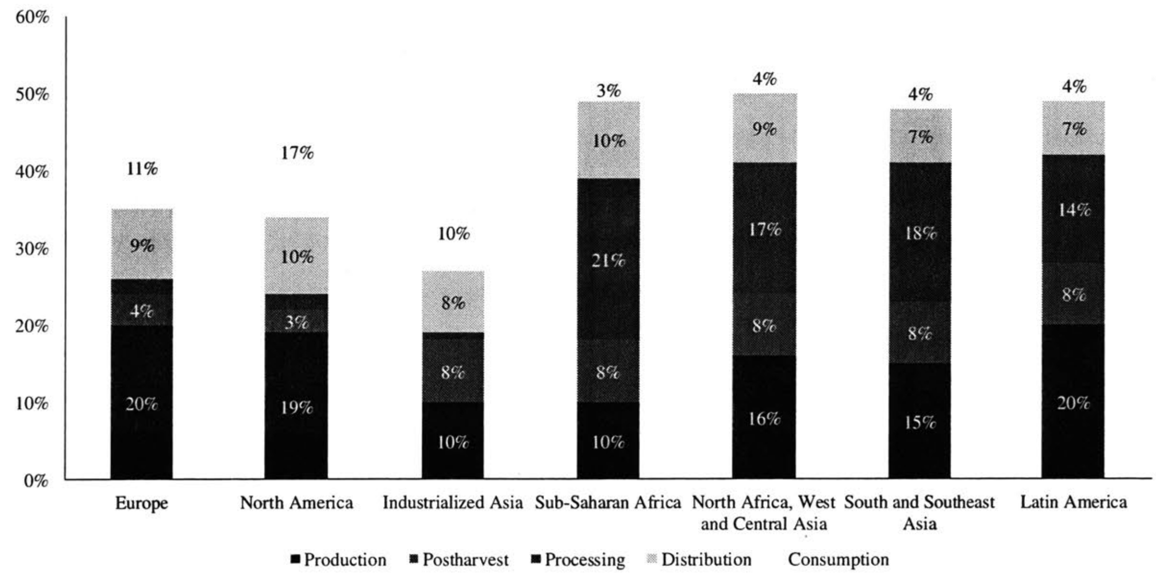

Figure 16. Percentage of food loss and waste at each phase of the food supply chain for fruits and vegetables [44].

Across the supply chain and various geographical areas, food production phases (production, postharvest and processing) are the most conducive to food waste. 47% - 79% of food is wasted or lost between the farm and its distributor [45]. This highlights the extreme vulnerability of farmers and food processors as opposed to the rest of the actors in the food value chain (input providers, distribution and retail companies, and consumers).

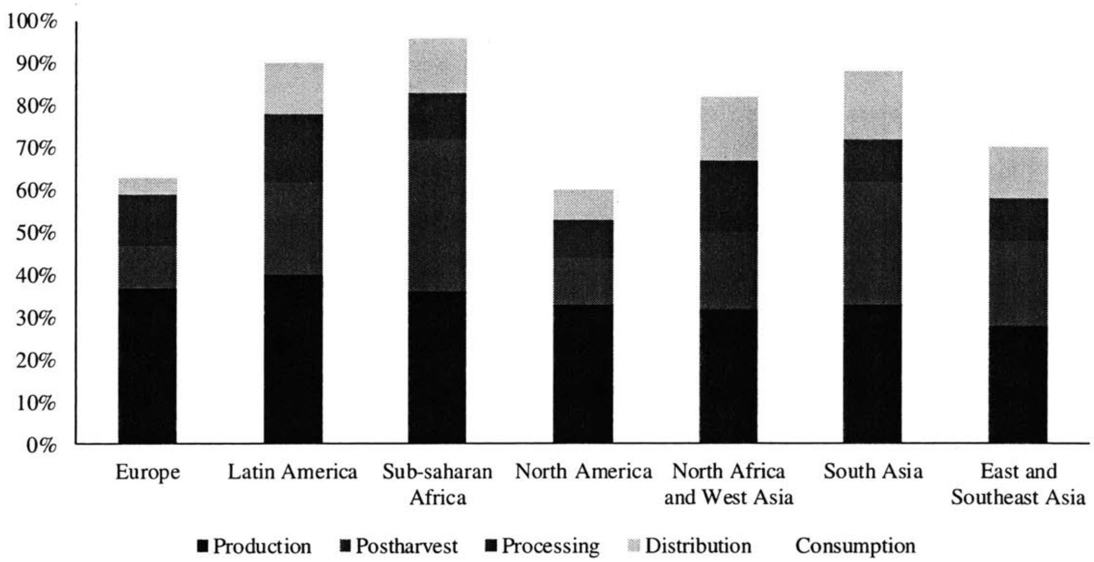

Figure 17. Relative contribution of each food chain stage to food waste and loss [45].

The scale and volumes involved in food waste are overwhelming. They now represent 8% of global greenhouse gas emissions [9,43,46], and appear increasingly paradoxical as there were 821 million people around the world considered undernourished in 2017 [11]. To respond to this situation, the United Nations set international goals to halve food waste by 2030 [43].

2.4.2 Causes underpinning food loss and waste

The Boston Consulting Group (BCG) has conducted significant research efforts to identify the main causes of food waste and loss across the food value chain, and to propose potential solutions. Five causes stood out from their analysis:

1. Awareness: There is low awareness of the public into the extent of food loss and waste throughout the value chain. This is especially acute among consumers, but also restaurants, hotels and food service providers. Consumers, for instance, keep demanding fresh produce in all seasons because they believe it is healthier, when in fact, it is more often the case for frozen produce [43]. Furthermore, discounts on grocery products encourage purchasing, which systematically fuels food waste [43].

2. Supply chain infrastructure: Cold chain is too often lacking in many developing countries, thus leading to early-stage storage conditions that diminish shelf life, and lead to significant food loss [43].
3. Supply chain efficiency: The low adoption of digital supply chain tools and food loss tracking solutions among farmers and food companies leads to avoidable food loss [43].
4. Collaboration: Lack of coordination and cooperation among players in the industry, especially growers and processors lead to significant waste [43].
5. Policy environment: Disposing of food waste remains very cheap, and tax policy does not penalize companies for the waste they generate, nor does it incentivize waste reductions [43]. Furthermore, expiration dates are very conservative and cosmetic standards too stringent, which often lead to large amounts of food ending in landfills [43]. Standards for imported foods differ among countries, making it difficult for producers to export when there is a drop in demand [43].

Additional causes of food waste will be analyzed in the later parts of this work, along with proposals of potential solutions.

2.4.3 The benefits associated with food waste reduction

Efforts to reduce food waste would trigger benefits for multiple actors of the food value chain, and enhance agricultural sustainability. Halving food waste by 2030, as proposed by the UN, would put the amount of food wasted or lost at 15-20% of food produced globally. The amounts of food saved would help bridge the food gap towards 2050, and alleviate the pressure that lies on producers to keep increasing productivity. Furthermore, the food that is not lost or wasted would represent a significant revenue or profit opportunity for farmers and food processors, whose finances are the most affected by this phenomenon. This stands true across the value chain, as a recent study showed that the benefit to cost ratio for food waste reduction programs was 7:1 in restaurants [47].

Besides obvious, yet significant economic incentives, food waste reductions would also contribute to enhancing agricultural sustainability. The global carbon footprint of food waste was 3.3Gt of CO_2 equivalent (excluding land use change) in 2007 [46]. As a country, food wastage would be the third emitter, after the US and China [46]. Similarly, the global water footprint of food wastage in 2007 was 3.6 times the blue water footprint of total US consumption, derived from the footprint of agricultural production [46]. This represents almost three times the volume of Lake Geneva, or the annual discharge of the Volga River. In 2007, the total amount of food wastage occupied nearly 1.4 billion hectares, or 28% of the agricultural land area [46]. In terms of surface, food wastage would rank second among countries, behind the land area occupied by Russia. Overall, reducing food wastage would diminish the pressure on natural resources, and improve the sustainability of current agricultural practices.

Population growth, the depletion of natural resources, and the increasing shortage of farmers pose extreme challenges to agriculture. Food waste represents a vast pool of opportunities to remedy this situation, but reducing it will not be enough. Additional breakthrough solutions will be needed to ensure global food security, and transition agriculture into sustainable intensification. Disruptive innovations and technological advances have the potential to upheave current industry paradigms, reduce the dependence on inputs, improve farmers' profit levels, and increase productivity.

3 Evaluation of the impact of AgTech

Responses to address the challenges faced by Agriculture have taken multiple forms. National governments have enacted bills to support income levels and farming communities, as exemplified by the US in 2018. Regional cooperation has led to the implementation of wide-ranging legislation and support, such as the Common Agricultural Policy launched in 1962 by the European Union (EU). Public support has fueled scientific research and technological innovations, through land grants or funding. One particular response, driven by innovative technologies, entrepreneurship and venture funding has intensified over the past decade, and will be the focus of the following parts of this work. This response will be referred to as AgTech, an umbrella term that encompasses the technological and entrepreneurial developments in Agriculture of the past decade. According to AgFunder, an online venture capital platform, an unprecedented $55.5 billon have been invested in food system ventures since 2012, a number that is still on the rise [48]. Many believe that AgTech could have a far-reaching impact on the global food supply, and be an effective solution to multiple challenges faced by Agriculture. AgTech has shown strong potential to help relieve pressures on the agricultural industry, and has delivered benefits ranging from yield increases to food safety enhancements. Nevertheless, it has also shown limitations, and is facing challenges that could hamper its impact. Several factors can explain these shortcomings, such as the common deficiencies of AgTech startups, the concentration of the agricultural industry, and the lack of expert and patient venture capital funding. In comparison to the amount of funding received by AgTech ventures, little effort has been put into tackling food waste, despite it being a vast pool of opportunities to ameliorate the sustainability of the global food supply. Developed countries, and especially the US, will be the main focus of the following parts of this work because of their prominence in AgTech. However, situations in other geographical regions and developing countries will also be explored.

3.1 Technological advances and direct benefits

Scientific advances are not new to Agriculture. This industry has fueled cutting-edge genetic research, machinery development, and agronomic progress with far-reaching spillover effects in other sectors. However, AgTech has marked the beginning of a renewed interest in agricultural innovation that stems from an unprecedented wave of investments, entrepreneurial ventures, and change. It is currently stretching the boundaries of Agriculture, and proposing new food production and consumption models, with significant benefits to farmers and consumers alike.

3.1.1 Origins, definition and recent traction

In the venture and financing worlds, the attention to AgTech skyrocketed after the acquisition of Climate Corporation by Monsanto for nearly $1 billion in 2013 [49]. This event marked the advent of a novel sector, and sparked interest for an industry that many deemed ready for change and innovation. In the background, a factor that has led to renewed interest in Agriculture is the increasing connectivity of farmland, especially in the US. According to the USDA, 71% of US farms currently have internet access, while 73% of farmers report to have computer access and 39% use a tablet or smart phone for farm business [50]. This trend paved the way for the implementation of novel digital solutions, ranging from farm management software, to connected sensor networks for farm-level analytics, and to real-time predictions that support farming decisions. The development of such solutions had been a longstanding goal in the industry. Born out of the increasing necessity of growing more with less, *precision agriculture* solutions such as yield monitors and Variable Rate Technology (VRT) have been under development since the 1990s. AgTech has also ignited a wide-ranging wave of funding and innovation in other related fields. Novel solutions in genetics, biochemistry and food processing have been developed by startups, and AgTech quickly became a multi-faceted sector with multiple applications.

This has made defining AgTech increasingly complex, and not just limited to the *conjunction of Agriculture and Technology*. According to AgFunder, *AgTech is a broad category ranging from farm-level analytics to genetics and biochemistry to food processing* [51]. For the entrepreneur group Start Up Australia, the term means *transforming the global food system* through digital technology [52]. For James Nielsen, Monsanto Australia technology lead, *AgTech is about smart farmers getting smarter using digital technology* [52]. For others, such as the Australian Farm Institute (AFI), AgTech is about *connecting things that have been around for some time* [52]. For the AFI research general research manager Richard Heath, *it's about things like yield monitors, spray monitors [..] and using the data they produce more efficiently and for a wider range of purposes* [52]. The difficulty to find a unique definition for AgTech is in fact highlighting the wealth of applications stemming from this sector. In an effort to categorize investments, AgFunder has developed a list of the application domains of AgTech. They are separated into two clusters: upstream technologies (ranging from agricultural biotechnology, to farm management software and to innovative foods) and downstream technologies (such as restaurant marketplaces, home and cooking technology, restaurant technologies…etc.). See Figure 19Figure 18 below for the entire list. The later parts of this work will primarily focus on upstream technologies and agricultural production, although several downstream solutions will also be analyzed.

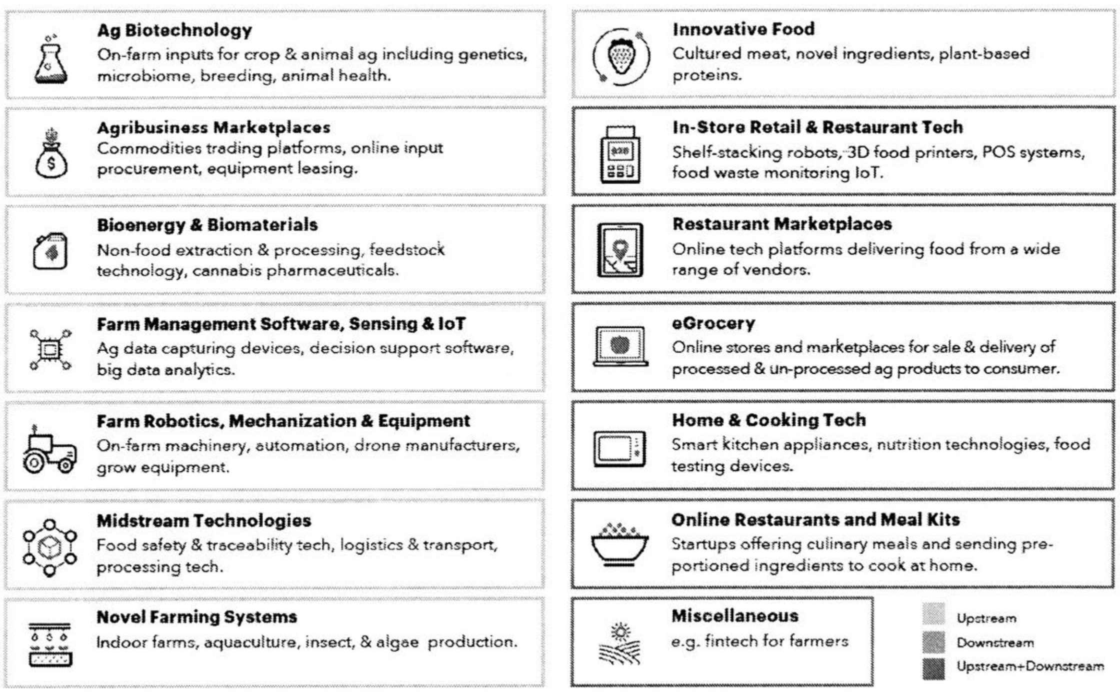

Figure 18. AgTech application domains, as defined by AgFunder. Figure taken from [48].

As mentioned above, an unprecedented wave of investments has fueled the development of AgTech in the past decade. Since 2012, annual AgTech funding has surged by 550%, from $2.6 billion in 2012 to $16.9 billion in 2018, at an average annual growth rate of 37% [48].

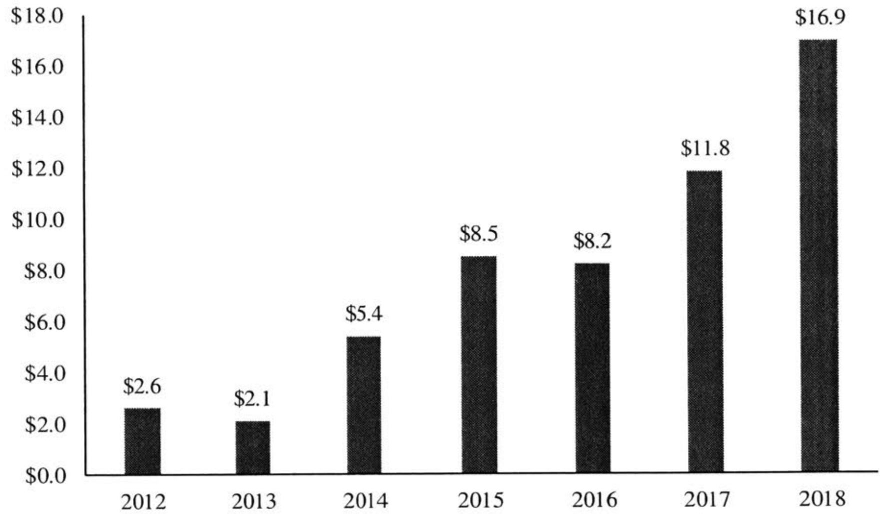

Figure 19. AgTech funding activity since 2012 (billion dollars) [48].

While upstream technologies received the lion's share of AgTech funding in the early 2010s (e.g. 85% of funding in 2012), this trend has reverted to let downstream technology dominate AgTech funding in recent years (59% of annual funding between 2016 and 2018) [48].

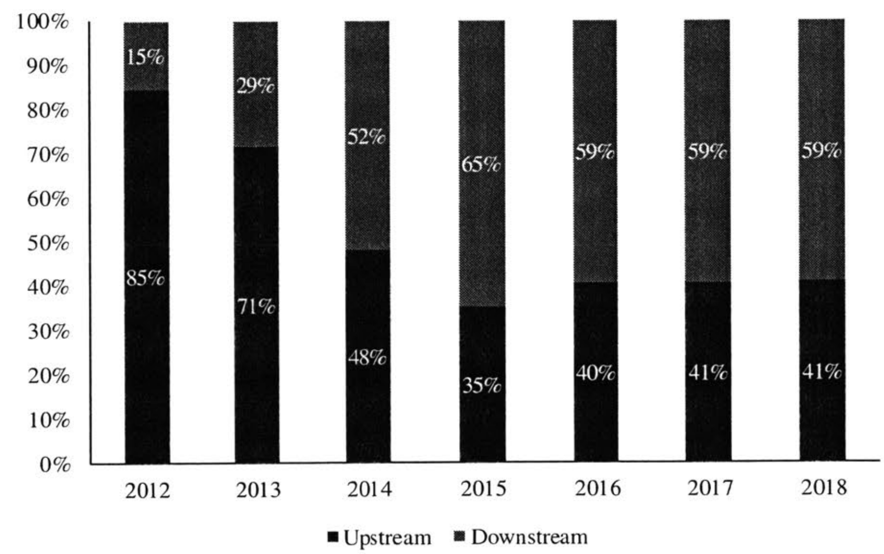

Figure 20. Breakdown of AgTech funding between upstream and downstream solutions [48].

Despite a 4% decline between 2015 and 2016, there has been a steady and significant growth in AgTech funding for the past three years, at an annual average rate of 27%, highlighting the financing sustainability of the sector [48]. AgTech funding has rapidly expanded to increasingly diverse applications, such as restaurant marketplaces, agricultural biotechnology, and novel farming systems [48].

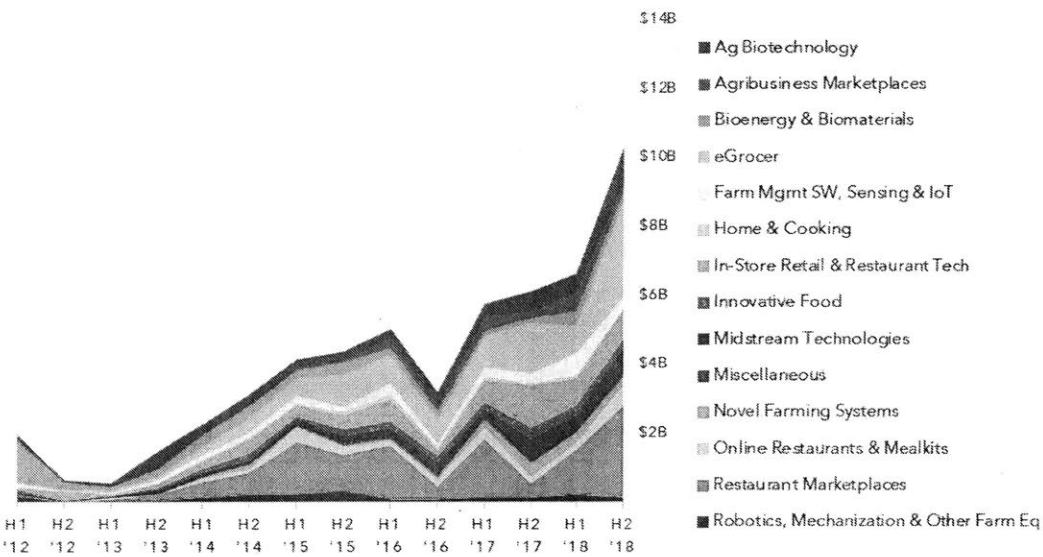

Figure 21. Evolution of AgTech funding by application. Figure taken from [48].

In 2017 and 2018, eGrocer companies (online stores and marketplaces for the sale of agricultural products to consumers) attracted 24% and 21% of the funding levels, respectively [48]. Similarly, other downstream solutions such as restaurant marketplaces received 21% and 23% of AgTech funding in 2017 and 2018 [48]. Upstream technologies, such as agribusiness marketplaces and agricultural biotechnology have maintained steady funding levels, attracting altogether 15% and 19% of investments between 2017 and 2018 [48].

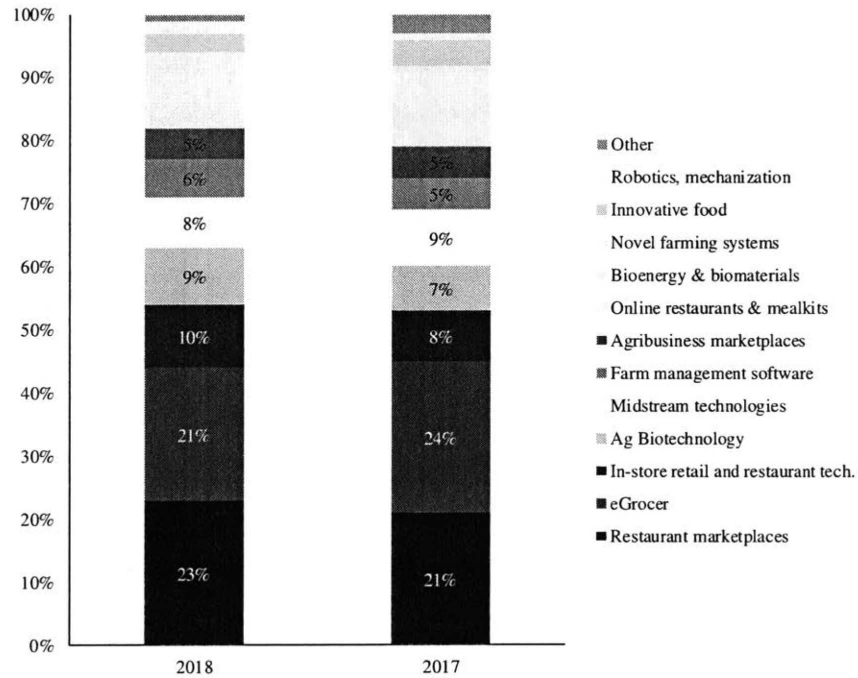

Figure 22. Breakdown of AgTech funding in 2017 and 2018 [48].

This diverse, fast-growing and unprecedented wave of private funding in agricultural ventures has brought about a number of solutions that stretch the boundaries agricultural practices.

3.1.2 The expansion of boundaries in agricultural production

The following part of this work presents a non-exhaustive selection of innovative AgTech solutions, and the possibilities that they create for the future of food production.

As mentioned above, Precision Agriculture solutions predate the dawn of AgTech, based on an initial need to grow more food with less. Tom Rogers' almond farm in California is a champion of these solutions [53]. His farm is reportedly *wired up like a lab rat* [53]. Moisture sensors monitor the soil, and their measurements inform the farm's automated irrigation system, which has allowed Rogers to cut water use by 20% since he adopted this technology [53]. Farms are increasingly turning into factories, where precision and efficiency are paramount. Similarly, Kip Tom, a seventh-generation family farmer in Indiana is often described as a Chief Technology Officer, rather than a farmer [54]. *I'm hooked on a drug of information and productivity*, he said to Express News in 2014, in an office filled with computer screens and plans for a future computer network [54]. His farm runs on sensors in the combines, satellite-based GPS data, self-driving tractors and apps for irrigation on iPhones [54]. This has allowed him to compete with giant agribusiness companies, and raised his return on investment, from 14% to 21.2% in just a year [54]. Through these solutions, farmers now have the ability to precisely measure input levels, monitor crop growth and take preventative measures that increase their efficiency.

Novel farming systems such as vertical farms push the resemblance with factories even further. Although they may not be the future of mass-market farming, they offer a valuable alternative for year-round fresh produce farming in urban environments. Mike Zelkind, CEO of vertical farm company 80 Acres Farms, claimed in 2016 that *his stacked shelves of crops are fresh, raised without pesticides and consumed locally within a day or two of harvest* [55]. Through the intensive use of LEDs, the company has reportedly managed to grow 200,000 pounds of leafy greens annually in a 12,000-square-foot warehouse, an amount that would generally require 80 acres of farmland [55]. Farming in controlled environments has allowed companies to greatly reduce input levels, land and water use, while boasting higher yields than conventional farming. Bright Farms claims that they can grow leafy greens with 80% less water, 90% less land and 95% less shipping fuel than lettuce grown in California and shipped to the east coast [56]. Indoor farming companies also boost farming research efforts through innovative methods. Freight Farms, an indoor agriculture company offers a real-time transparency feature, which enables the traceability of a single head of romaine through every growing stage, back to the hour when the seed was planted [57]. They also distribute what they call growing recipes to farmers, which allow them to replicate ideal environmental conditions for specific crops [57].

Another novel and fast-growing field in AgTech has been the development of microbial solutions to make crops more resistant, and find substitutes to pesticides and fertilizers. *I think there is a future in which we use less than half of the chemical fertilizer we use today, and we may eliminate as much as 90% of the chemical insecticides and fungicides* said David Perry in 2018, the CEO of Indigo, a microbial agriculture company founded in 2014 [58]. Indigo has been leveraging advances in DNA sequencing and machine learning to analyze microbes and identify those that can help plants resist crop stresses such as drought, salinity, nutrient deficiency, pests and diseases. Specifically, they claim that specific microbes can allow a cotton plant to withstand drought conditions [58]. Similarly, Pivot Bio has been working on the discovery and development of microbes that can produce nitrogen. They are re-discovering long-forgotten microbes with a natural ability to sustainably feed plants [59]. They claim that their science has *the potential to one day replace the need for synthetic nitrogen fertilizer for cereal crops* [59]. Another company, AgBiome, has developed a vast microbial collection, through which they were able to identify microbes and proteins that kill insects, fungi and weeds with a higher efficacy than existing chemicals [60]. Should they deliver on these claims, microbial solutions could upheave farming paradigms, and greatly improve agricultural sustainability and food security.

Recent developments in gene editing, namely the birth of CRISPR/Cas9 gene-editing methods, offer similar possibilities. They allow researchers to develop novel varieties with groundbreaking proprieties. In 2018, a joint team of American and Chinese scientists used gene-editing technology to develop a rice variety that produced 25-31% more grain than average [61]. They claim that this variety would have been impossible to create through traditional breeding methods [61]. Similarly, Chinese scientists have developed varieties of rice that can be grown in seawater, potentially creating a novel food supply for 200 million people [62]. Although genetic research is not new to Agriculture, novel gene-editing techniques coming from orthogonal industries expand the possibilities for plant breeding.

Increasing rural connectivity has opened farmland to novel services, such as field-level analytics that enhance management and profit maximization. For instance, Granular delivers profitability insights at the field level, as well as guidance on farmland prices [51]. It claims that it can help producers improve profitability on every acre, optimize input levels and maximize soil productivity [63]. Similarly, Climate FieldView (formerly known as Climate Corporation) helps farmers visualize critical field data, and manage field variability by building customized fertility and seeding plans for fields to optimize yield and maximize profit [64]. Farmers Business Networks is an independent farmer-to-farmer network of thousands of American farms [65]. This company spreads farm information by aggregating anonymous analytics, and shares profit enhancing farm analysis [65].

3.1.3 Direct benefits to the global food system

Besides expanding the realm of possibilities through innovative technology, AgTech solutions have delivered direct benefits to the global food system, from farmers to consumers. One landmark, less recent case, is the adoption of GMO crops. According to a 2014 analysis mentioned by the FAO, on-farm GMO adoption has reduced chemical pesticide use by 37%, increased crop yields by 22%, and enhanced farming profits by 68% [4].

More recent AgTech solutions, albeit less adopted within farmers, have claimed significant yield improvements as a result of their product. Based on 2018 field trials, Pivot Bio claims that it can outperform fields using synthetic fertilizer by 7.7 bushels per acre (bu/acre), while preventing nitrates from leaching into waterways [66]. Indigo claims significant yield increases across five major crops through its proprietary microbial solutions: +14% for cotton, +9% for soybeans, +6% for corn, +7% for rice, and +13% for wheat [67]. Furthermore, it asserts that producers growing *Indigo Wheat* with a 40 bu/acre average can potentially earn $44.20 more per acre in the 2018/2019 season [67].

Other AgTech solutions have claimed significant cost savings. Precision agriculture technologies such as yield mapping, guidance systems and VRT led to cost savings of 4.5%, 2.7% and 3.7-3.9% respectively, according to a 2016 USDA study [68]. The automated weeding solution developed by Blue River Technology allegedly eliminates 90% of herbicide volumes currently sprayed by growers, thus leading to large cost reductions [69]. Through their network buying power, Farmers Business Networks helped a grower achieve a 50% price reduction on chemicals, compared to usual price levels [65]. Produce Pay allows farmers to receive payments for their products the day after they are shipped, instead of after a common 30-45 day waiting period, thus delivering significant short-term financing savings to farmers [56].

AgTech solutions can thereby lead to higher profit levels and net returns. A recent evaluation of yield mapping, guidance systems, and VRT conducted by the USDA showed that these three technologies led to returns higher by 1.8%, 2.5% and 1.1% respectively [68]. In developing countries, AgTech solutions also help farmers optimize yield and profit levels. Ricult, a holistic platform designed to help farmers connect directly with buyers and purchase inputs, among other services, affirms that it has delivered 50% yield improvements and 30-40% profit increases to its users on average [70].

Finally, AgTech solutions can also benefit consumers by enhancing food safety and traceability. The startup FoodLogiQ currently provides supply chain analytics to 7,000 food companies to ensure that their products are safe to consume [56]. Clear Labs developed a DNA sequencing solution to verify a food's ingredients, its GMO status, and whether it is contaminated by harmful pathogens before it reaches a consumer [71].

Overall, AgTech solutions have had a wide-ranging impact on food production systems. They have pushed the boundaries of agricultural production, and delivered clear benefits to producers regarding yield, cost, and financial returns. Should these benefits materialize on a wide scale through large adoption among farming communities, AgTech could improve global food security, relieve pressures on natural resource bases, and enhance farming income levels.

3.2 Current limitations and future challenges

Despite numerous successes, AgTech has also shown some limitations and is facing significant hurdles to establish itself as a true disruptive force in the agricultural industry. AgTech is suffering from the slow-paced adoption of many technologies on farmland. The financial incentives of many solutions are often too low for farmers to invest in them, especially in a context of thin income margins. Finally, AgTech has yet to upheave an industry that remains controlled by giant agribusiness companies.

3.2.1 Decreasing user engagement and slow-paced technology adoption

Although expectations are still high for many, AgTech has also suffered from a decreasing user engagement and slow-paced technology adoption. In 2018, industry analysts stated that the need for innovation in agriculture had never been greater [72]. As input and labor costs rise, and as commodity prices continue to stagnate, analysts deem that there is increasing recognition that new solutions are needed to relieve farming businesses from financial pressures [72]. A number of farmers believes that AgTech is meeting these expectations, as one in Iowa stated in 2017:

We've really been able to use our data to make better decisions and manage it within certain areas, manage it, analyze it, benchmark it, and be able to find profitability [73]. Nonetheless, doubts have surfaced, along with a certain fatigue regarding AgTech solutions. Finistere Ventures, a venture capital firm specialized in AgTech investments wrote in 2018: *The jury is out on whether this wave of innovation will lead to strong market adoption. Farmers demand a step change in value; only startups delivering on a clear value promise will be able to scale and drive profitability* [74]. Industry experts report that small farmers can be overwhelmed by many of these new products and services, often linked to complicated contracts, not compatible with existing equipment or growing practices, and promising solutions to problems that farmers do not necessarily face [75]. *A lot of the technology is really promising,* stated Tyler Scheid in 2017, who has received many pitches from AgTech startups [75]. *But a lot of it is really impractical for the ag setting*, he added [75]. Because of this inadequacy with the needs of producers, there have even been talks of an AgTech bubble. *It's going to burst if it keeps going the direction it is,* said Aaron Magenheim, CEO of AgTech Insight, to Fortune in 2017 [75]. Similarly, Kleiner Perkins partner Brook Porter stated in 2017 that t*here has been an overexuberance about the opportunity, and I think there will be a lot of failures* [75].

As a counterpoint, AgTech can still be considered in its infancy, with only over a decade worth of experience. This is perhaps best exemplified by the lower than average failure rates observed in agricultural ventures so far. According to BLS Business Employment Dynamics data, agricultural startups founded in 2011 had the highest survival rate after 5 years (66%), compared to rates between 45-55% for industries like mining, retail, manufacturing, or financial services [76]. Similarly, statistics taken from the Statistic Brain Research showed that agricultural startups ranked third in survival rates after 4 years of operation (56%), compared to 58% for finance insurance and real estate, or 47% for retail [77]. This evidences the dynamism and resilience of the AgTech entrepreneurial ecosystem, which still has tremendous potential.

However, AgTech is suffering from the slow adoption of many technologies on farmland. As reported by AgFunder in 2019, Matt Crisp of Benson Hill stated that *there are many technologies on the market, but adoption is not as fast as expected* [78]. Growers often hesitate to invest in unproven innovations, as they have low margins and a limited amount of time to assist the technological development [78]. Novel agricultural systems must clearly respond to a need to convince customers: increased efficiency and competitiveness, simplification of operations, or cost reductions [78]. Slow-paced adoption has plagued precision agriculture technologies in the past. As reported by Finistere Ventures in 2018, *self-steering tractors and combines, for example, are less than 20 percent adopted after a decade or more of effort* [72]. Technologies developed in the 1990s such as yield monitors, guidance systems, GPS mapping and VRT, albeit with proven benefits, often took more than 10 years to establish themselves the farming industry. Specifically, although yield monitors have been rapidly adopted among corn, soybeans and rice farmers in the US between 2001 and 2013, they have not been adopted by more than 10% of US cotton producers so far [79]. It can be worse, as often the adoption of some of these technologies can stagnate for decades. GPS soil mapping technology and VRT have not reached 30% adoption in major US crops in nearly 20 years [79]. Figure 23, Figure 24, Figure 25, and Figure 26 below provide more details on the adoption of these technologies among crop growers in the US.

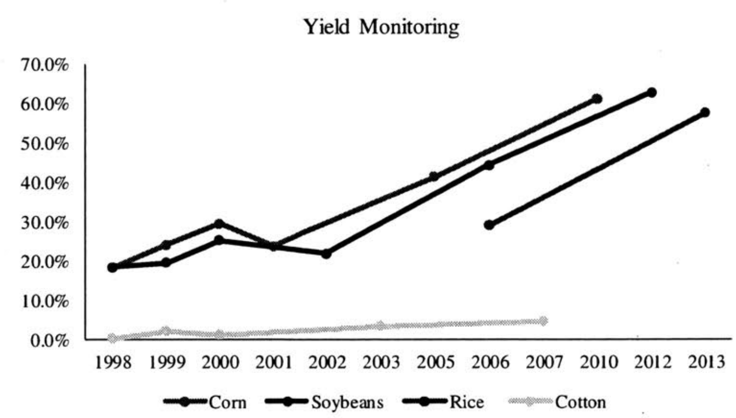

Figure 23. Adoption of yield monitoring solutions in major crops in the US (percent). Data from [79].

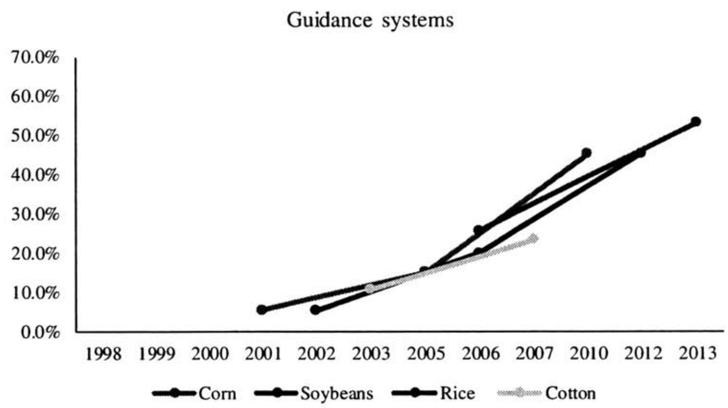

Figure 24. Adoption of guidance systems in major crops in the US (percent). Data from [79].

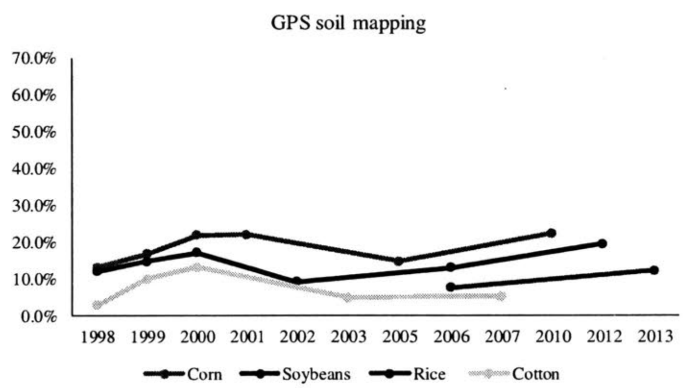

Figure 25. Adoption of GPS soil mapping in major crops in the US (percent). Data from [79].

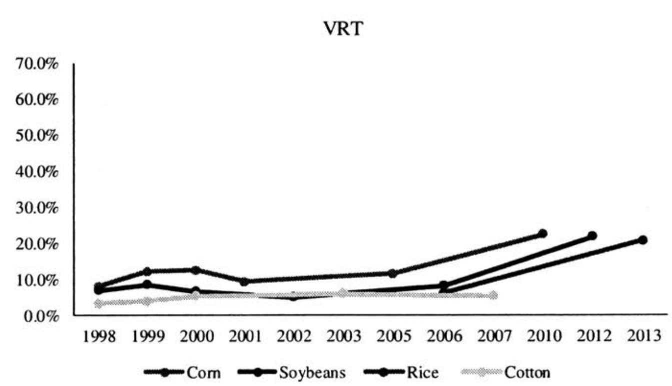

Figure 26. Adoption of VRT in major crops in the US (percent). Data from [79].

This data evidences how uneven the rate of adoption of novel technologies can be on farmland. This is especially acute when looking at the adoption of technology per farm size. According to 2016 USDA data, GPS mapping and guidance systems have been adopted by 80% and 84% of US farms larger than 3,800 acres, respectively [68]. In comparison, they have been adopted by 12% of US farms smaller than 600 acres [68]. Similarly, VRT has been adopted by 12% of farms smaller than 600 acres, as compared to 40% for farms larger than 3,800 acres [68]. Table 17 below provides additional detail on these differences.

Table 17. Breakdown of adoption rates for Precision Agriculture technologies on US farms, by farm size [68].

	GPS mapping	Guidance systems	VRT
Less than 600 acres	12%	12%	12%
600 - 1,000 acres	34%	24%	20%
1,000 - 1,300 acres	39%	33%	18%
1,300 - 1,700 acres	50%	40%	23%
1,700 - 2,200 acres	54%	60%	32%
2,200 - 2,900 acres	49%	60%	32%
2,900 - 3,800 acres	67%	78%	29%
Over 3,800 acres	80%	84%	40%

This observation is also true for solutions that have penetrated the agricultural market more recently. Certain farm-level analytics solutions have experienced rapid adoption, as exemplified by the 120 million acres managed by Climate FieldView after a decade of operations [80]. In comparison, less than 10% of farmers recently surveyed by the USDA made their irrigation decisions based on soil moisture sensors [81]. Less than 1% used computer simulation programs to do so [81].

3.2.2 Low financial incentives for farmers to invest in AgTech solutions

AgTech solutions often focus on yield improvements and farm data analytics, which have received the lion's share of publicity in recent years. However, this has led to a neglect of farm profit maximization, which systematically takes precedent in a farmer's decision to invest in technology. Organizations have even called for startups to focus on other challenges than yield improvements, especially in developed countries. James Bell-Bouth, General Manager of Sprout, an AgTech startup accelerator based in New Zealand, raised similar concerns in 2018: *It's a pet peeve of mine when people reference that we need to feed 10 billion people by 2050 as the biggest issue we face — it's completely missing the point* [82]. *Population growth is happening in developing countries which are facing a totally different set of challenges to the developed world*, he added [82]. Similarly, the focus of AgTech on data analytics has spurred criticism by industry analysts. Seana Day, partner at the Mixing Bowl said to Finistere Ventures during a Q&A session in 2018: *Growers don't really care about data. They care about whatever that will give them either more time or make them more profitable. The companies that really understand that dynamic and how to translate their value into dollars and cents will have the best shot, because they're able to provide links between field productivity and monetary results* [72]. As a result, doubts on the value of data analytics solutions have intensified. *Everybody is still trying to figure out where the value in data is,* said Aaron Ault, a corn and soy farmer on 3,000 acres in Indiana to the Wall Street Journal in 2017 [83]. A potential reason behind this is the lack of integration between technology solutions and accounting software on farms. As one farmer told Agthentic in 2018, *It's hard or even impossible to know the ROI on some of these [farm management] tools, when we can't connect them to our financial systems....we literally don't know if they're helping us make decisions that save money* [84]. Certain AgTech solutions have not delivered the returns that farmers expected, thus lowering the incentives to invest in them, especially in a context of thin margins. *I'm tired of paying for technology that doesn't pay me back*, expressed a farmer interviewed by Farmers Business Networks in 2017 [73].

The defiance of farmers towards yield improvement solutions can be explained by the fact that it has not historically led farmers to higher profits. It has even been the opposite in the past 50 years. Total Factor Productivity (TFP) has tremendously increased since the 1940s. It has risen by 250% since 1948, and by 78% since 1980 [85]. Figure 27 below provides more detail on the surge in TFP since the 1960s.

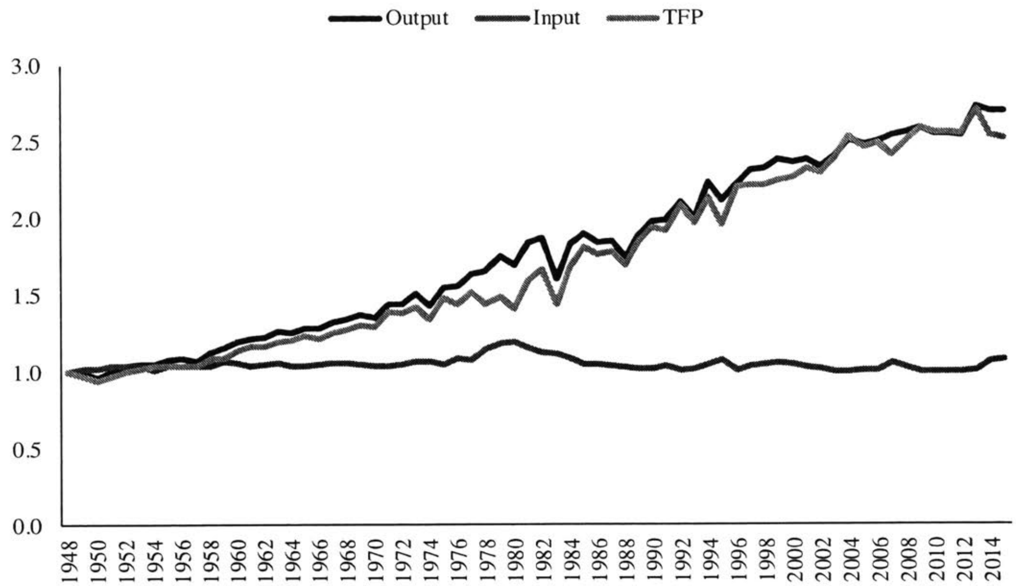

Figure 27. Output, input and Total Factor Productivity indices, as computed by the USDA. Data from [85]. *TFP takes into account all of the land, labor, capital, and material resources employed in farm production and compares them with the total amount of crop and livestock output. If total output is growing faster than total inputs, then the total productivity of the factors of production (i.e., total factor productivity, or TFP) is increasing. TFP differs from measures like crop yield per acre or agricultural value-added per worker because it takes into account a broader set of inputs used in production. Definition given by the USDA, from [83].*

However, input suppliers have captured most of the value stemming from these productivity improvements. Between 1960 and 2018, farming cash expenses went from 64% of gross cash income to 78% in the US [86]. Over the same period, labor expenses have remained stable at around 18.5% [86]. The increase in cash expenses has been largely driven by a surge in input prices. Specifically, seed expenses rose from 3.5% of gross cash income to 11.1% over the period [86]. Fertilizer expenses increased from 8.9% to 10.9%, and pesticides grew from 1.9% to 7.9% [86]. Direct government payments have supported farming margins up to a certain point, but they have not managed to prevent farm income margins from decreasing by nearly 50% between 2013 and 2018 [86]. On average, input suppliers have even captured more value than they were generating through productivity improvements. Furthermore, maximizing yield often requires the fine-tuning of many facets of a farmer's production, which can be time-consuming and too complex. Farmers will tend to avoid investing in technology solutions with unproven benefits to their bottom line, even if they show potential to increase productivity. Figure 28 and Figure 29 below provide more detail on the evolution of farm cash expenses and net farm income.

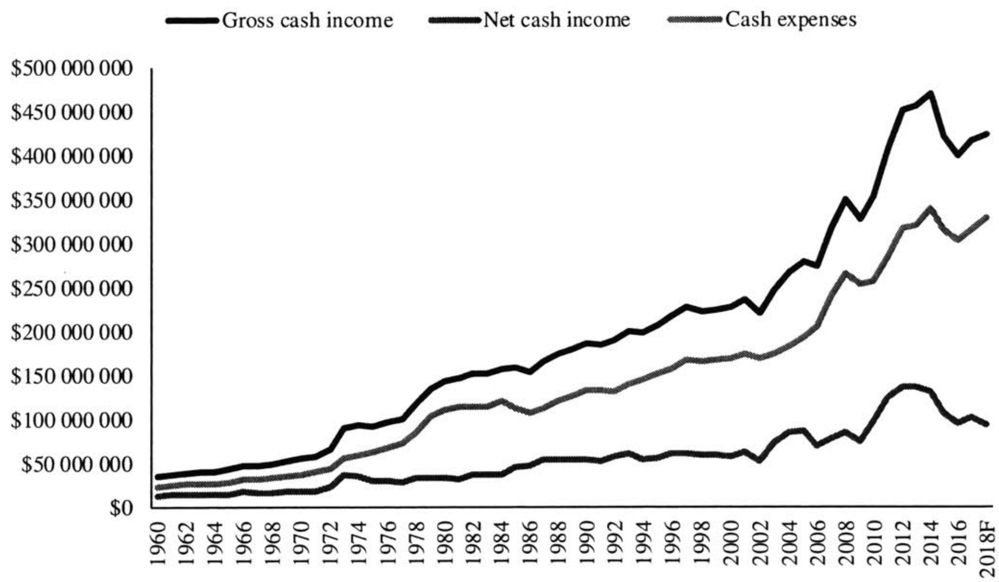

Figure 28. US farming gross cash income, net cash income and cash expenses [13].

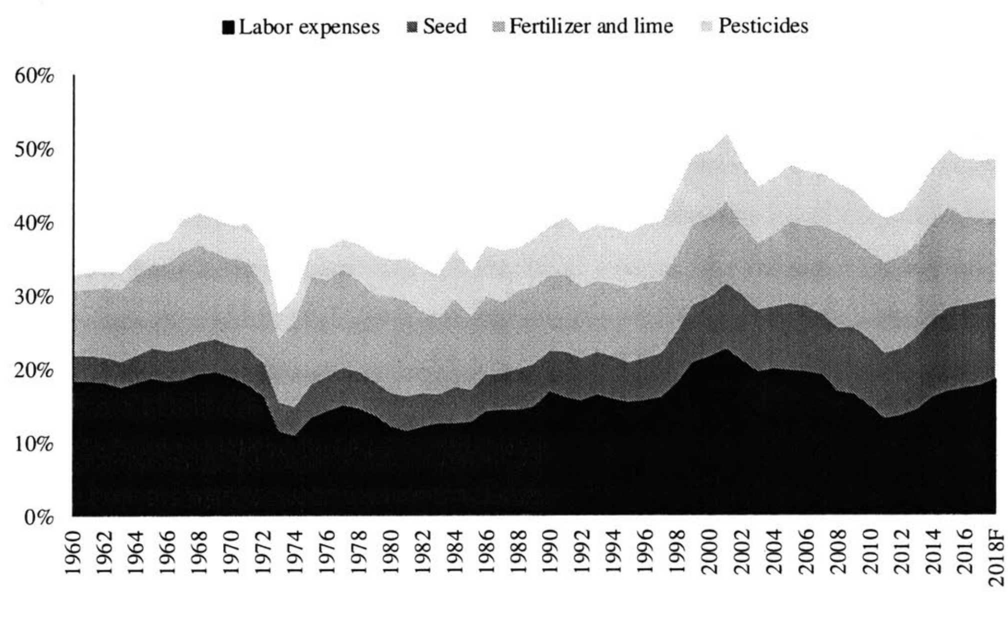

Figure 29. Evolution of a selection of cash farming expenses (percent of gross cash income). Data from [86].

Fast-growing input prices and unstable commodity prices have led farmers to incur losses on major crops. Except for soybeans, most crops have delivered losses to farmers since 2013 in the US, with a record -$100/acre for wheat in 2017 [87]. See Figure 30 below for more detail.

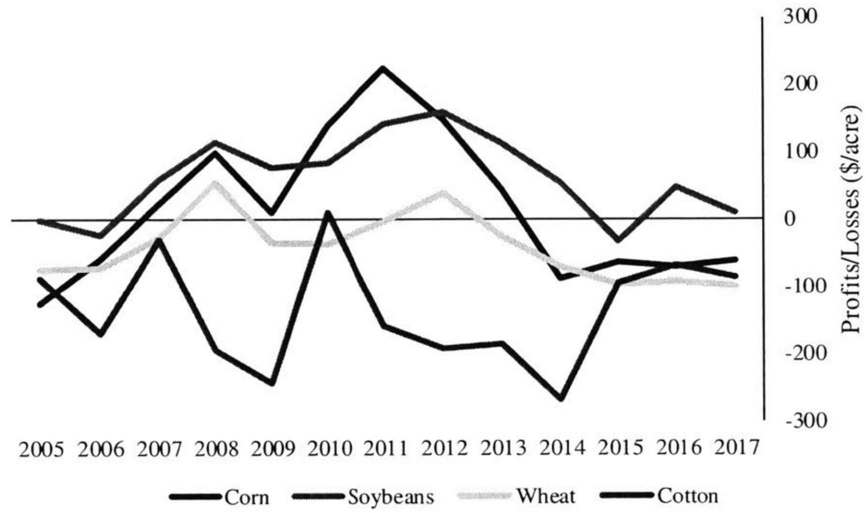

Figure 30. Profits/Losses ($/acre) of US farmers on major crops. From [87].

These trends have even pushed farmers to take radical action, and eliminate products with proven benefits from their production systems, because of prohibitive costs. As stated by a corn and soybean grower in Illinois in 2017 to Farmers Business Networks, *I know a couple guys have grown non-GMO to reduce seed costs and have done it without any decrease in yield* [73].

Furthermore, multiple AgTech solutions have been estimated to push farmers to bear increasing financial risk and scale their operations, to the detriment of profit maximization. This increases the divide between small farms and large farms, the latter being the only ones able to take such risks. Specifically, equipment costs have surged because of the integration of sensing and communications technology with machinery. Notably, a combine equipped to harvest a few crops would cost around $65,000 in the 2000s; now it can cost up to $500,000 because of the added technology [54]. While this has triggered an uptick in productivity for larger farms, yields in smaller farms have not followed suit because of their inability to invest [54]. Additionally, technological solutions allegedly push farmers to grow single crops at the largest possible scale to maximize the effectiveness of technology [54]. Ann Thrupp, executive director of the Berkeley Food Institute, a policy and technology research institute at the University of California, Berkeley, event went further in 2014: *Technology encourages farmers to move too aggressively toward easy-to-grow and easy-to-sell crops that are more easily measured by instruments, rather than keeping some diversity in the fields — an age-old hedge against bad weather and pests* [54].

Overall, many AgTech solutions are yet to trigger a wide adoption among farmers. Yield improvement solutions can make farmers defiant: they have historically brought about a decline in profits, and they generally push farmers to take significant risk. Data analytics solutions on the other hand have to clearly demonstrate value creation if they are to convince farmers.

3.2.3 Current limits to the impact of AgTech on Agriculture

The overall impact of AgTech, although promising, sometimes seems limited, especially among growers. Doubts about AgTech solutions have sometimes turned into a reluctance to participate in the entrepreneurial ecosystem. Growers in the US reportedly roll their eyes when they hear about cost savings and yield increases, because every startup has the same sales pitch [88]. *Consider the farmer that has watched the billions of dollars being poured into AgTech over the past 10 years and is still struggling to make a margin. With this in mind it's not difficult to empathize with why they're not excited with the next new gadget to give them more data. That is, unless that data goes further to an actual better decision. More specifically, a decision that will make them more profitable*, wrote Tim Hammerich for futureofag.com [88]. The overwhelming amount of supply of technology solutions has also led farmers to become tired of having, as one farmer described to Agthentic in 2018: *a new sales guy calling me or showing up every week with a new product that I have no interest in, and that's not even fully developed* [84].

In parallel, AgTech has not yet managed to disrupt giant agribusiness companies, especially in the US. 95% of AgTech exits have taken the form of a Merger & Acquisition (M&A), thus interrupting the incorporation of new technologies into distribution channels and farmer networks [89]. The acquisition of Blue River Technology by John Deere in 2017 is a case in point [90]. The company had spent multiple years developing its automated weeding solution with vegetable farmers in California, before Blue River decided to exit this market and focus on cotton crops. The M&A is often commanded by agribusiness giants like Monsanto or Syngenta, retail leaders like Wilbur Ellis and Winfield, or farm hardware specialists like AgCo and John Deere [89]. This has allowed these firms to maintain a robust control on their industries. Furthermore, these exits, albeit highly publicized, have been relatively few. The long-term impact of AgTech will be defined by its ability to generate a larger number of them, as well as a broader validation by capital markets in the form of Initial Public Offerings (IPO) [72].

3.3 Factors underlying the difficulties of AgTech

What follows below is an attempt to identify several factors that explain the shortcomings and hurdles that AgTech has been facing. Some of them are inherent to the Agriculture industry, and will be further analyzed in later parts of this work, such as the lack of large-scale research to provide farmers with compelling proof-of-concepts. Nevertheless, other factors proceed from common deficiencies of AgTech startups, the inertia caused by the increasing concentration of agribusiness companies, and the initial absence of adapted funding sources to AgTech ventures.

3.3.1 Common deficiencies of AgTech startups

AgTech startups have often displayed similar flaws from their inception. First of all, AgTech entrepreneurs often fail to engage early with farmers, and have a limited knowledge of the industry, leading to crucial mistakes. Reportedly, the most common mistake of AgTech entrepreneurs is not to spend enough time and energy to create a complete understanding of Agriculture [91]. In parallel, there is a significant lack of industry knowledge at the start-up and investor knowledge, which often leads to unrealistic assumptions in business models [91]. According to the Illinois Soybean Association (ISA), one of the main hurdles to successful AgTech innovation is the under-representation of the producer's voice [92]. Their perspective could provide entrepreneurs with valuable insights on product development, the definition of the business model and value sharing with producers, as well as go-to-market strategies [92]. As reported by Connie Bowen and Sarah Nolet for Agfunder in 2019, *AgTech is useless if we cannot engage farmers; [...] the question of how farmers and the AgTech community of entrepreneurs, investors, and accelerators can work together to build great products is much harder to answer*

[93]. This situation partly stems from the challenges to engage with farmers early on. Farmers have relentless workloads, and extremely busy schedules [93]. Furthermore, they have to constantly manage an overwhelming number of variables, ranging from weather to disease to trade policy, which limits their availability to support innovators [93]. Often, entrepreneurs have pushed unfinished products on the agricultural market, which has led farmers to feel reluctant to contribute to entrepreneurial ecosystems [93].

Second of all, AgTech startups have often failed to reduce the complexity of managing a wealth of new technologies. Agronomists and growers are often drowning in data because of the influx of novel solutions [94]. Satellite imagery, on-farm sensors and application maps generate more data on a daily basis than what a human operator can analyze [94]. Although this data is a source of valuable insights for farming decisions such as fertilizer applications, AgTech startups have failed to help farmers analyze it and develop actionable recommendations [94]. This complexity often proceeds from three factors: the disjointed nature of datasets preventing effective contextualization of agricultural data; time-consuming low-level data visualizations and interpretation hindering the timely generation of agronomic insights and recommendations; and the disconnect between proven crop science and modern enterprise-scale farming [94]. Overall, the multiplication of AgTech solutions and providers has led their management to become increasingly challenging for producers. This is perhaps best illustrated by Figure 31 below. This 2014 drawing shows the overwhelming number of technology solutions that Kip Tom, a farmer in Indiana, has to manage on his operation. This is especially challenging as farmers often do not have enough time to delve into data analytics. As voiced by an Illinois farmer in 2017, *capturing the precision agricultural data that's something we've had since the beginning, but not a lot has actually been done with it. I don't have time to devote weeks at a time to really delving into stuff, with farming, it's seasonal, and when it comes harvest, you don't have time for computer work* [73].

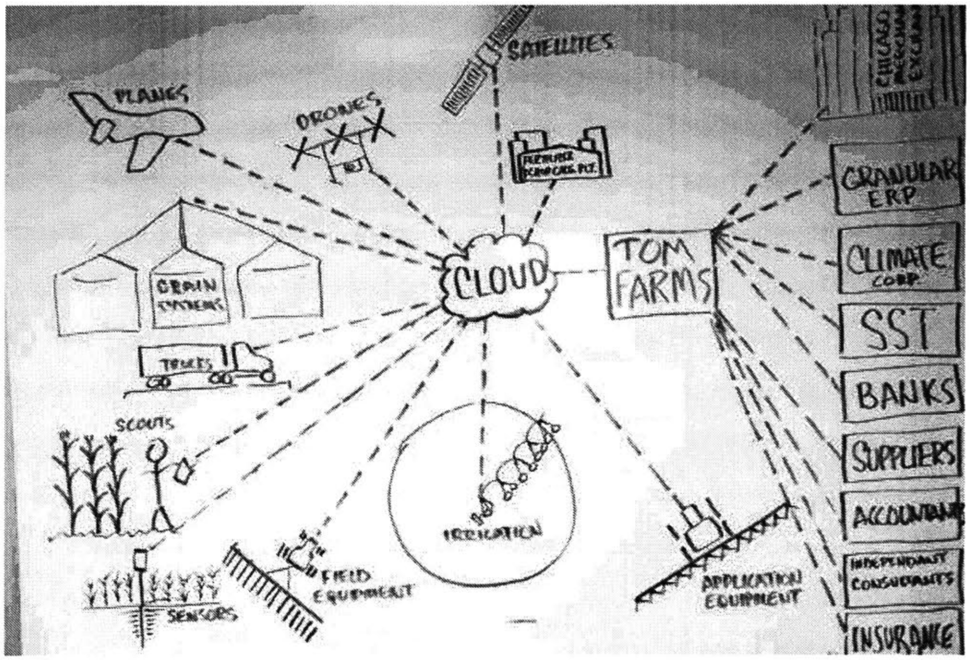

Figure 31. A drawing by Kip Tom details the use of technology in the business operation at Tom Farms. From [54].

Finally, many AgTech startups have failed to address critical data-related concerns, which can have significant repercussions on the decision to adopt a new technology. Farmers often have troubles trusting data, have concerns on ownership, and on the compatibility of data infrastructure with existing platforms [78]. A joint study led by the USDA and the US Department of Homeland Security has identified three threats that farmers are especially concerned about. First, farmers take the confidentiality of their information very seriously: they are protective of yield data, land prices and herd health [95]. Second, data integrity can be a source of worries, as producers install sensor networks in their crop, equipment automation, robotics, and machine learning [95]. Finally, data availability is a concern: farming equipment relies increasingly on complex communication and guidance systems, which can be vulnerable to cyber-related threats [95]. A 2016 survey by the American Farm Bureau highlighted the extent of these concerns. 77% of surveyed farmers were concerned about which entities could have access to their farm data and whether it could be used for regulatory purposes [96]. 67% of farmers stated they considered how outside parties use their data when deciding which technology to use [96]. 61% of farmers are worried that companies could use their data to pressure market decisions [96].

Overall, the lack of early farmer engagement, the increasing complexity of managing technology solutions, and the absence of a response to data-related concerns have been widely reported as common AgTech startups deficiencies.

3.3.2 The inertia of the agriculture industry

Another critical factor behind some of the shortcomings of AgTech is arguably the inertia of the agriculture industry, fueled by decades of concentration. An increasingly small number of agribusiness players now controls most of the stages in the food value chain, ranging from farming inputs, to food processing, and to farm equipment. As voiced by a corn and soybean farmer in Nebraska 2017 to Farmers Business Networks, *we're getting down to three companies that are going to control most of the seeds and the chemicals. Lack of competition could be something that's going to affect us in the future.* [73]. Currently, the largest four corn seed providers control 85% of the market; three tractor suppliers control 95% of their market; and the largest four grain traders have a 90% market share [73,97]. Figure 32 below provides additional detail on the industry concentration per segment. A quote, still exact, by John Fitzgerald Kennedy offers an acute description of this situation: *the farmer is the only man in our economy who buys everything at retail, sells everything at wholesale, and pays the freight both ways* [98]. According to the Open Markets Institute (OMI), this situation has been the main driver of the recent rise in input costs, decline in output prices, and the subsequent profit decreases for producers [97]. It has produced a farm crisis across America on an unprecedented scale since the 1980s, according the OMI [97].

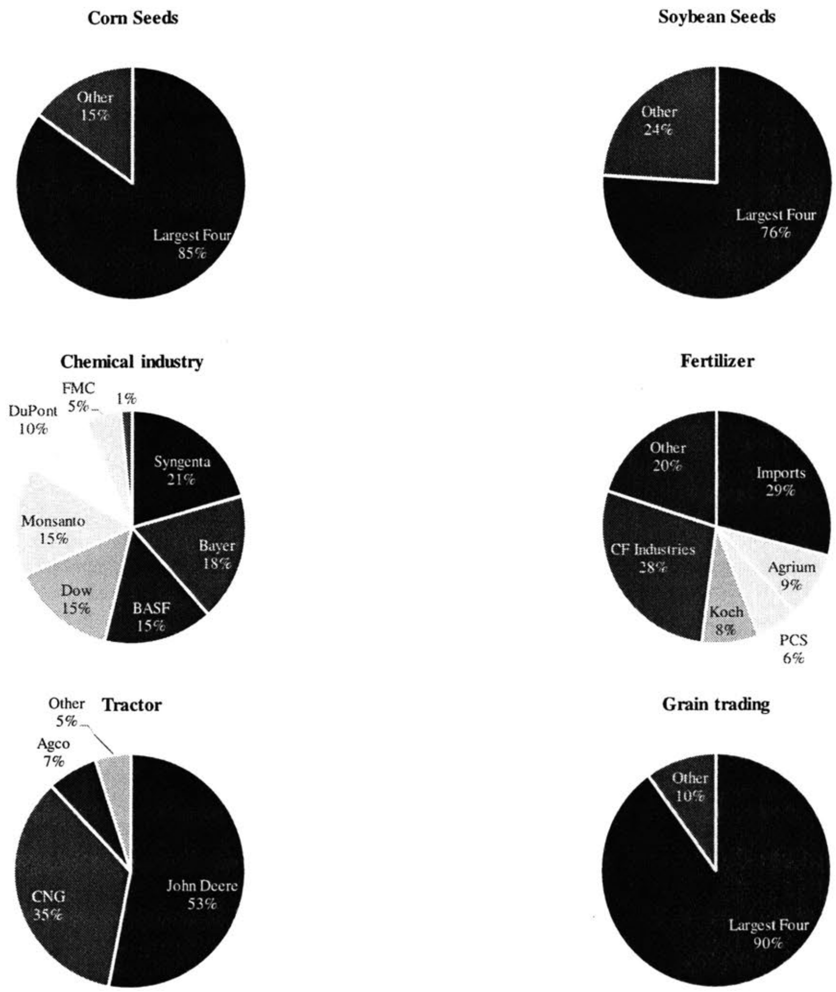

Figure 32. Concentration of the food value chain, by segment. From [73,97]

The recent consolidation of the world's Big 6 agribusiness companies (BASF, Bayer, DuPont, Dow Chemical, Monsanto and Syngenta) has made matters worse. Monsanto merged with Bayer in 2016 to create a conglomerate in seeds, biotechnology and agricultural chemicals [99]. Similarly, Dow Chemical and DuPont finalized their merger in 2019 [100]. Table 18 below provides additional details on these mergers and the expected sales of the merged entities. The Big 6 has turned into a Big 4 with an even higher control on agricultural sectors.

Table 18. Mergers conducted by the world's 'big 6' agribusiness companies. From [101].

Company	2015 sales (Seeds and biotech)	2015 sales (Ag. Chemicals)	Proposed merger partner
BASF	Small	$6,211m	None
Bayer	$819m	$9,548m	Monsanto
Dow Chemical	$1,409m	$4,977m	DuPont
DuPont	$6,785m	$3,013m	Dow Chemical
Monsanto	$10,243m	$4,758m	Bayer
Syngenta	$2,838m	$10,005m	ChemChina

Such a strong concentration can hamper the pace of change and innovation in the industry. As highlighted by the USDA in 2017, *there is good reason to think that increases in concentration do not persistently lead to greater incentives to innovate; rather, beyond some high level of concentration, further increases could actually reduce the incentive to innovate* [101]. This has also put pressure on food startups looking for exit strategies, leaving them only with one of two choices: limit their growth to niche markets, or get acquired to expand to supermarket shelves [97]. AgTech startups face similar pressures, as giant agribusiness companies have been highly active in M&A and venture capital to lower their risk of disruption. This has allowed them to capture innovative solutions early, as highlighted by their M&A activity described below in Table 19. Notably, Monsanto acquired The Climate Corporation in 2013, and DuPont acquired Granular in 2017 [48].

Table 19. AgTech M&A led by agribusiness giants. Data from [48].

Target	Acquirer	Year	Amount
Antelliq	Merck	2018	$2.4bn
The Climate Corporation	Monsanto	2013	$930m
Agraquest	Bayer	2012	$425m
Blue River Technolgoies	John Deere	2017	$305m
Granular	DuPont	2017	$300m
Pasteuria Biosciences	Syngenta	2012	$113m

Large strategics have also intensified their venture capital activity to monitor the AgTech sector. Monsanto and Bayer backed two of the earliest AgTech venture capital funds (Cultivian Ventures and Finistere ventures), respectively [102]. Syngenta, Monsanto, DuPont and Bayer have started

AgTech investing arms, dating back to 2006 for Syngenta [102]. The prominence of agribusiness giants in venture capital funding and M&A often leads AgTech startups to focus on productivity improvements that do not benefit farmers. The latter constitute the core business of large agribusiness firms, who have been the only available options to AgTech startups for exits. This is magnified by the relative absence of other funding mechanisms for AgTech startups, such as Private Equity or public capital markets.

3.3.3 The initial absence of adapted funding for AgTech solutions

Another factor that may have played a part in the shortcomings of AgTech is the initial lack of expert and patient funding. AgTech funding was initially driven by traditional venture capital players who were not specialists in Agriculture. 11 AgTech transactions were closed in 2009, out of which the majority was funded by traditional technology venture capital firms, namely Kleiner Perkins Caufield & Byers (KPCB), Khosla Ventures and Andreessen Horowitz [102]. In 2018, Kleiner Perkins was still the most active investor in late-stage investments for the AgTech sector [72]. Currently, there is a large number of generalist investors placing tangential bets on AgTech through investments in drones, sensors, or satellite imagery [102]. Although there has been an increase in the number of AgTech-focused investment firms, this initial lack of expertise has had negative effects on the development of several AgTech ventures. Specifically, there has been a lack of alignment between market needs and investment flows [72]. This has led segments such as crop protection, input management, and farm analytics to receive the lion's share of funds over recent years, as segments such as plant science and animal technologies have been underinvested, although they generally deliver higher value to investors and farmers [72]. Furthermore, and perhaps more importantly, venture capital firms often lacked patience with AgTech investments, thus putting additional pressure on already strained early-stage ventures [78]. Patience is paramount in Agriculture, where it can take a long time to develop a prototype and collect real world field trial data [103]. As opposed to consumer technology, AgTech startups often only have one opportunity a year to sell to farmers. These long sales cycles can often make scaling and demonstrating profitability challenging. This has often pushed entrepreneurs to opt for rapid exits, sometimes to the detriment of product development and customer relationships. Although the situation has largely improved lately, AgTech has suffered from the early absence of an effective funding ecosystem to scale new technologies on farmland.

3.4 The limited focus of AgTech on food waste reduction

There has been a marked increase in efforts to tackle food waste, ranging from private and public funding, to policy initiatives and innovations in recent years. However, these efforts are still limited in comparison to the amount of attention and funding in AgTech. This is especially surprising since food waste reduction represents one of the biggest economic and environmental opportunities in the food system.

3.4.1 Recent developments in food waste reduction initiatives

Increased consumer awareness and the wave of funding and innovation in AgTech have spurred the interest of investors and entrepreneurs in food waste reduction [104]. This has led private and public funding to rise in recent years. Notably, startups aiming to reduce food waste have landed $125 million in venture capital and private equity funding in 2018 in the US according to ReFED, a collaboration of more than 50 business, nonprofit, foundation and government leaders committed to reducing food waste [104,105]. Notably, Apeel Sciences, which develops products aimed at extending produce shelf life received $70 million in new financing [106]. Food Maven and Full Harvest, two business-to-business (B2B) marketplaces for excess or visually less appealing foods have each received $8.5 million in funding [106]. This also extends to countries outside the US: Swedish company Karma closed $12 million in funding for its app that helps grocery businesses and restaurants sell produce at the last minute [106]. French-based company Phenix, which helps sort excess product and sends it to donation, animal feed, or recycling centers, landed €15 million in funding [106]. Similarly, public and philanthropic funding for food waste reduction initiatives has surged. Foundation grants for food waste reduction groups reached $134 million in the first three quarters of 2016, a 70% increase over 5 years [104]. Out of this, $20 million were specifically targeted towards food waste reduction initiatives, the triple of philanthropic support since 2012 in the US [106]. The increased awareness about this issue is exemplified by the Rockefeller Foundation, who recently launched a $130 million initiative to fund grants [105]. *If we are able to advance a more sustainable, less wasteful food system, we will preserve precious planetary resources and create more opportunities to nourish the 41 million Americans that currently lack consistent access to food* said Devon Klatell, Food Strategy Lead and Senior Associate Director at The Rockefeller Foundation in 2018 [106]. In addition to philanthropic funding, over $100 million has been contributed to food waste reduction programs from local governments, mainly in California [106].

In parallel major food businesses have made commitments to food waste reduction, and governments have implemented novel policies to discourage food waste. In the US, the Congressional Food Waste Caucus, launched in 2018, proposed $25 million in annual funding for composting and food waste reduction pilots and research [104]. 12 American states now offer additional tax incentives to encourage food donations [104]. In 2014, the state of Massachusetts implemented a landfill ban, which had diverted 260,000 tons of food waste via compost, donation and wastewater processing by 2016 [104]. There have also been global initiatives to combat food waste. In 2012, the European Parliament passed a resolution to cut food waste by 50% in the European Union by 2025 [107]. The US government followed suit in 2015, and declared a 50% food waste reduction goal by 2030 [107]. More recently, the UN proposed to halve food waste by 2030 as part of the Global Sustainable Development Goals [107]. Simultaneously, large food businesses have intensified their commitment to reduce food waste through internal efforts and external partnerships [104]. Two thirds of the world's largest 50 food companies participate in programs with a food loss and waste reduction target [104]. 50% of the US retail market has committed to the national goal of halving food waste by 2030 [104]. Notably, Kroger's recent social impact plan (Zero Hunger | Zero Waste) includes a promise to eliminate all food waste in stores by 2025 [104]. This increased interest in food waste reduction has financial grounds for these companies, since they often represent costs that can diminish their competitiveness [104].

In parallel, there has been an acceleration of market-based initiatives and innovations aimed at tackling food waste. There is a growing number of corporate incubators and startup accelerators, exemplified by the Chobani Incubator, or the month-long startup program FoodTrack, recently launched by Maersk [104]. Several successful innovation case studies have boosted the traction around food waste reduction. Harps Food stores increased their margin by 65% and sales by 10% in avocados after piloting Apeel Sciences' solutions [104]. Imperfect Produce, a marketplace that sells visually less appealing produce has recorded $180 million in sales, just three years after its launch [104]. Thanks to a product developed by Spoiler Alert, food startup HelloFresh reduced its landfill bound food waste by 65% [104]. According to ReFED, *the food waste innovation* *sector is an exciting and rapidly changing space [...] Continuing to support pilots, innovation, and capacity building will be important for the next few years* [104].

3.4.2 Food waste reduction efforts remain limited in comparison to AgTech

Funding activity, albeit increasing, is still not enough to meet food waste reduction goals. According to ReFED, there should be an annual total investment of $1.8 billion in the US to reduce food waste by 20% over the next ten years [104]. Out of this amount, an annual $650 million should come from private funding sources (venture capital, private equity, project finance). Thereby, the $125 million invested by private investors in 2018 only meet 20% of this requirement. Similarly, ReFED estimates that an annual $290 million should come from philanthropic investors [104]. However, only $134 million were raised in the first three quarters of 2016 [104]. Furthermore, ReFED points out that the majority of this philanthropic funding has been poured into food recovery and food banks, and not food waste reduction initiatives [104]. Overall, the total $258 million funding activity reported by ReFED in the US seems relatively small in comparison to the $16.9 billion invested in AgTech ventures in 2018. This highlights lagging efforts, and the lack of appropriate funding and support to accelerate the development of food waste reduction innovations.

Additionally in the US, several organizations have pointed out the absence of a comprehensive action plan to promote wide-scale national reduction in food waste, despite a pledge to halve it by 2025 [104]. Experts believe that food waste measurements are insufficient and often inconsistent, which might make reaching food waste reduction goals more challenging [104].

3.4.3 Food waste reduction remains an untapped pool of valuable opportunities

This situation is especially surprising as food waste reduction represents a pool of highly valuable economic opportunities. Besides its ability to improve global food security, farming profitability and agricultural sustainability, as mentioned in 2.4.3, food waste reduction could also deliver significant economic benefits, at the macro and micro scale.

In the US, ReFED has shown that an $18 billion investment into 27 food waste reduction solutions could yield $100 billion in societal economic value [104]. Over 10 years, this investment would trigger $60 billion in consumer savings, $19 billion in business profit, and the creation of 15,000 jobs in the US [104]. In addition, these measures would help recover 18 billion meals, conserve 16 trillion gallons of water and reduce GHG emissions by 180 million tons [104]. Major investors have even recognized these economic opportunities, such as Andreessen Horowitz, S2G Ventures, Cultivian Sandbox Ventures, and DBL Partners. *Food waste is a huge problem hidden in plain sight, investing in it is one of the best economic and environmental opportunities in the food system* said Chuck Templeton, Managing Director, S2G Ventures [106]. These opportunities also materialize at the micro scale. A report by the WRI has shown that food waste reduction investments have a 7:1 benefit to cost ratio for restaurants [47].

The lagging investment in food waste reduction initiatives might be another illustration of the control exerted by agribusiness companies on the global food supply chain. Currently, the top four grocery chains have a 44% market share of US food retail [97]. This has primarily affected farmers, who have suffered from a sharp decline in output prices. In 1990, ranchers received $0.59 of each dollar spent on beef, a number that has decreased to $0.31 today [97]. Similarly, processed food manufacturers have merged into an oligopoly over recent years. Namely, Unilever and Kraft Heinz sell 80% of US mayonnaise, and PepsiCo sells 60% of all chips [97]. This control results in a situation that can be detrimental to farmers, who often face supply control practices and fluctuating wholesale orders. In the US, it has been reported that growers can suffer from ungrounded product returns from retailers. *I can tell you for a fact that I have delivered products to supermarkets that was [sic] absolutely gorgeous and because their sales were slow, the last two days they didn't take my product and they sent it back to me* said the owner of a mid-size east coast trucking company to the Guardian in 2016 [108]. *They will dig through 50 cases to find one bad head of lettuce and say: 'I am not taking your lettuce' when that lettuce would pass a USDA inspection*, he added [108]. As a result, it has been estimated that US farmers leave 7% of produce unharvested in fields each year, in an attempt to hedge against weather, disease and fluctuating wholesale and retail orders [109]. If more retailers worked directly with farmers, or encouraged their intermediaries to collaborate with them, agricultural food waste could be greatly reduced [109].

Overall, AgTech has been a formidable proponent of change and new solutions to challenges faced by Agriculture. It has opened up novel possibilities in agricultural production, and has delivered clear benefits to stakeholders across the global food supply chain. Although AgTech is facing difficulties on its path to completely transform its industry, there are multiple avenues to overcome them and potentially enhance its impact.

4 Recommendations to enhance the impact of AgTech

The following parts of this work will propose recommendations to surpass challenges AgTech is facing, and potentially enhance its impact. The first three parts will focus on different levels: ventures; innovation ecosystems (comprised of universities, entrepreneurial communities, investors and growers); and the whole Agriculture industry. The final part of this work will propose a potential solution to food loss and waste in agricultural production.

4.1 Ventures: focus on solutions that primarily benefit farmers

AgTech startups must primarily target on-farm value creation if they are to be widely adopted by producers. As mentioned in 3.2.2, AgTech ventures often provide insufficient financial incentives to motivate investments. This often stems from the misalignment of the product with the needs of growers, for instance an excessive focus on yield improvements to the detriment of profit optimization. However, technology adoption can be extremely fast when it addresses the needs of growers and clearly demonstrates value creation. It is thereby pivotal for ventures to identify the most pressing needs of growers, and leverage available resources that facilitate customer research and product development.

4.1.1 The rationality of farmers on technological investments

Because of extremely thin margins, often negative returns, and the risks associated with them, growers are highly rational about technological investments. This is perhaps best explained by a quote given by Lisa Prassack, a prominent figure in AgTech consulting, to the Weekly Times in 2017: *Basically if something is too difficult, it's not going to happen. If it's easy, and it answers a question, then it will be adopted. And you have to be able to show [...] measurable outcomes they can use now, not distant promises that might not come to fruition* [52]. When AgTech solutions clearly demonstrate value, on-farm adoption is fast-paced. Notably, the acres under management of Farmers Business Networks, Climate FieldView and Farmers Edge have grown at average annual rates of 82%, 24% and 259% between 2014/2015 and 2018. After only 600,000 acres in 2014, Farmers edge claimed 100 million acres of farmland under management in 2018, or close to 32% of the total US harvested cropland [110,111]. Similarly, Farmers Business Networks claimed it had 30 million acres under management in 2018, just 4 years after its launch [112]. Table 20 below provides additional detail on the rapid expansion of these companies. The key to their success has often been the same: farm profit improvements, whether they stem from cost optimization, higher output prices, or lower input expenses.

Table 20. Acreage under management of AgTech companies. Data from [80,110–120]

In million acres	**2014**	**2015**	**2016**	**2017**	**2018**	**'14-18 - CAGR**
Farmers Business Network						
Acreage under Management	NA	5.0	9.0	16	30	**82%** *
% US harvested cropland	*NA*	*2%*	*3%*	*5%*	*10%*	
Climate FieldView						
Acreage under Management	50	NA	92	100	120	**24%**
% US harvested cropland	*16%*	*NA*	*29%*	*32%*	*38%*	
Farmers Edge						
Acreage under Management	0.6	NA	9.2	20	100	**259%**
% US harvested cropland	*0.2%*	*NA*	*NA*	*6%*	*32%*	
US Harvested Cropland	315	315	315	315	315	

*CAGR: Compound Annual Growth Rate; *: 2015-2018*

Farmers are increasingly technology savvy, and willing to take risks if the expected returns are compelling. According to a 2016 survey led by the American Farm Bureau, 75% of farmers stated that they plan to invest in new technologies in the next three years [75]. Although the average age of farmers has been on the rise, decision making in numerous farms is being passed down to younger farmers [121]. The latter have longer time horizons to experiment with new technologies, are thrilled about recent developments in AgTech, and already use cloud-based solutions like Farmers Business Networks [121].

Another key evidence of the rationality of growers about investments is their behavior when technologies are detrimental to their profitability. Farmers across the US have been hacking farm machinery since 2017, when equipment manufacturers decided to ban independent repairs on their machines [122]. Farmers perceived this as a severe threat to their businesses, and decided to take action [122]. *When crunch time comes and we break down, chances are we don't have time to wait for a dealership employee to show up and fix it* Danny Kluthe, a hog farmer in Nebraska, told his state legislature in 2017 [122]. This sparked a national movement that led to a countrywide battle between farmers, fighting for their right to repair, and equipment suppliers. In 2018, Jason Koebler, a Vice.com reporter, deemed it as *the biggest people versus big tech revolt in recent memory* [123]. The goal of this revolt is to propose laws that will allow farmers and consumers to recover ownership of their equipment [123]. At the beginning of 2019, numerous states, such as Nebraska, had proposed fair repair bills and were preparing for votes. *The Fair Repair act gives an individual the ability—you've always had the right—to purchase the diagnostic tools or to take their equipment somewhere local, or to try and repair the equipment yourself*, said Lydia Brasch, a state senator of Nebraska, to Jason Koebler about a law she sponsored in 2018 [123].

4.1.2 Identification of the needs of crop producers

It is essential for AgTech ventures to identify the needs of crop producers, and ensure that their product addresses them. What follows below is a description of three pressing needs of crop producers that stood out during interviews with farmers, researchers, investors and entrepreneurs.

AgTech startups must primarily focus on value creation, as highlighted by AgFunder's Barclay Rogers in 2016: *AgTech is here to stay. But given the contraction in agricultural markets, AgTech companies will need to be laser-focused on value creation. While much of the emphasis to date has been on field level optimization, applications that help maximize profitability, or that address broader agricultural markets, may prove to be of most value* [124]. In a context of thin margins, there is increasingly less room for experimentation: farming decisions must rely on financial grounds [92]. As opposed to yield maximization that has led margins to decrease on average, profit optimization, through cost reduction or differentiation, is a priority to most farmers. *I think cost reduction is probably the number one thing everyone is thinking about*, said a corn and soybean grower in Illinois to Farmers Business Networks in 2017 [73]. Cost decreases result from input optimization, the availability of cheaper substitutes, or increased bargaining power of farmers over the rest of the supply chain. As mentioned in 3.3.2, the concentration of the input industry has led to a surge in farm expenses. Novel solutions such as FBN Direct, created by Farmers Business Networks, have tried to revert this trend [65]. Through the aggregative power of its farm network, Farmers Business Networks has been negotiating lower input prices, leading to significant savings for its members [65]. Similarly, farmers look for solutions that help them meet their demand more effectively, or sell their crops at a premium. Companies like Agrible and Indigo have spearheaded efforts in this field. In 2018, Indigo launched a marketplace to directly connect grain growers with their buyers [125,126]. To allow producers to differentiate and enhance price transparency, Indigo has developed novel solutions that preserve the identity of crops throughout the entire supply chain [126]. As of February 2019, the marketplace totaled over $10 billion in supply inventory and over $16 billion worth of bids submitted, underlining significant market validation [126].

Second, AgTech ventures must lead to operational efficiencies, be they time savings, reduced management complexity, or lower employee turner. As evidenced in 3.3.1, the rising number of solutions providers has led to an overwhelming complexity for farmers. They often have dozens of tabs open on their computer to handle the different technologies on their farms, and generally do not have enough time to delve into each of them. As a result, farmers tend to proceed with caution when investing in new technology, which has slowed the adoption of innovations on farmland. Similarly, growers are looking for solutions that optimize the stability of their operations. In a 2017 profile by the Wall Street Journal, Lon Frahm, a crop producer in Kansas, had shared several insights into the success of his 30,000-plus-acre farm [127]. According to him, part of his success has relied on an empowering division of labor, leading to near-zero employee turnover in the past 30 years. Holistic solutions that help farmers organize their businesses more efficiently, handle interactions with suppliers, and enhance employee engagement are needed. However, they should come at little or no cost to farmers, because of their strained financial situations. Models such as the one proposed by Farmers Business Networks, which only charges $700 per year to its members, are the most likely to succeed [65].

Finally, AgTech solutions must also focus on enhancing farmland sustainability. Although profit optimization takes precedent in management decisions, farmers are conscious that their main asset is their land. Innovations that sustain soil health, or reduce the dependence on chemical inputs are crucially needed. They help maintain the value of land longer in the case of a sale or an inheritance, reduce the need for fallow, or alternatively allow farmers to transition into organic production more easily.

4.1.3 The necessity of listening to producers

As mentioned in 3.3.1, early-stage farmer engagement can be a key success factor for an AgTech venture. However, engaging with growers can be challenging because of their tight schedules, and the relative absence of ecosystems to do so. Still, there are multiple resources available to entrepreneurs for early-stage customer research, and product development. An increasing number of accelerator programs connects startups with interested growers, such as Thrive, The Yield Lab or AgLaunch. Universities like UC Davis have implemented early-stage programs to promote the collaboration of farmers, innovators and reseachers. These will be explored in more detail in the following part of this work. Farmers-led innovations, such as MagGrow (a spraying solution that reduces drift by 70%) or Farmers Business Networks provide valuable templates for rapid adoption and success in the Agriculture industry [65,128]. Finally, online farming communities provide entrepreneurs with stethoscopes to survey and analyze the industry. Namely, Farmhack has created a platform for collaborative research in open-source tools for farming equipment [129]. AgFuse has developed a networking site for the agricultural community to make business and social connections [130].

4.2 Innovation ecosystems: enhance cooperation between stakeholders

As mentioned in 3.3, the lack of cooperation between entrepreneurs, farming communities, researchers, investors, and government has hindered the development of AgTech. It is necessary to create ecosystems that foster collaboration in the food value chain, and accelerate the development of impactful innovations. These structures must be supported by adequate capital that is cognizant of the characteristics of the Agriculture industry. Israel's leadership in AgTech is an effective model for the development of such ecosystems.

4.2.1 Develop innovation clusters to foster collaboration

Collaboration between agricultural stakeholders can produce formidable results. When entrepreneurs, farmers, and researchers work hands in hands, they create ventures that present fewer flaws, gain early traction, and have a faster path to proof-of-concept. Farmers Business Networks, often publicized as one of the most successful AgTech ventures, is a case in point. The company was born out of the willingness of farmers to develop an objective farmer-driven information source [65]. After collaborating with technologists, scientists and entrepreneurs, the company launched its platform in 2014 and quickly received industrywide validation [65]. Four years later, in 2018, the company was reportedly about to generate $200 million in revenue, up nearly 200% from $72 million in 2017 [131]. Just like for most entrepreneurial ventures, success factors in AgTech often include the access to industry knowledge, early adopters, customer feedback, and investors. However this is often challenging for AgTech ventures, because of the lack of ecosystems that link these stakeholders.

Several organizations have led efforts on this front, and developed structures that could serve as templates for the rest of the industry. Specifically Thrive, a startup accelerator founded in 2014, has managed to bring together growers, investors, researchers and entrepreneurs through an innovative structure. Since its creation, Thrive has supported five startup cohorts, which altogether have raised $100 million in funding, amounting to an overall $500 million valuation [132]. It has received strong recognition from prominent figures in the Agriculture industry, such as Bruce Taylor, the CEO of Taylor Farms, who said about Thrive that it *helps bridge that gap between the know-how of Silicon Valley and the application here with growers in the Salinas Valley and around the world* [132]. As explained by its CEO John Hartnett to AgFunder in 2019, the success of Thrive is mainly a result of its holistic approach [133]. Thrive has built a platform based on four pillars: a startup accelerator, a venture fund, a corporate program, and an AgTech summit created with Forbes Media in 2013 [133]. To accelerate startups, Thrive has developed a network of 6,000-plus farmers that entrepeneurs can leverage for feedback on product development, and the conduction of field trials [132]. Furthermore, Thrive has partnered with the Western Growers Association (a California-based aggregation of producers) and its innovation center to help companies scale in the California region [133]. It has also developed relationships with prominent farming companies, such as Driscoll's, Taylor Farms, and Land O'Lakes to provide startups with access to potential business partners, or investors [132]. Similarly, AgLaunch, a non-profit startup accelerator in Memphis, partners entrepreneurs with growers to ensure that their product meets actual farmer needs [134]. They have built a network of producers to organize field trials, screen transactions, and receive support for investment decisions [134].

Agricultural universities have also been champions of collaboration between entrepreneurs, growers and researchers. In particular, University of California, Davis (UC Davis) has developed a range of programs that support the development and commercialization of innovative technology. As of 2016, UC Davis had created a hackathon called Apps for Ag to support the development of early-stage ventures in AgTech [135]. It had launched the UC Davis Venture Catalyst, which provides new ventures with legal services and funding [135]. It had also created a business incubator to help startups connect with growers interested in field trials, and partnered with a seed company to make 3,100 square foot of lab space and 1,800 square foot of greenhouse space available to entrepreneurs [135]. Furthermore, it recently announced plans for an Agricultural Innovation Hub, a facility where UC Davis researchers could unite with industry partners to accelerate technologies [136]. Other universities, such as University of California, Agriculture and Natural Resources (UCANR), provide farming communities with evaluations of startup technologies to support their investment decisions [137]. These evaluations also help startups develop compelling proof-of-concepts, which is often challenging in early stages.

Overall, these efforts must continue and lead to the development of innovation clusters that foster collaboration and innovation. A potential model industry for this could be the biotechnology sector in the US, with certain changes to fit the Agriculture industry. Agricultural innovation clusters could for instance involve (but not be limited to): government support through land grants for research and innovation and tax breaks; university partnerships to accelerate the transition of research-based technologies and support the generation of field proof-of-concepts; startup accelerators with ties to farming communities and agribusiness firms; incentives for growers to engage in product development; and incentives for entrepreneurs to relocate.

4.2.2 Funding innovative ecosystems with adequate and expert capital

A key enabling factor for these ecosystems will be the participation of sufficient private funding levels, along with a shift in investment theses. First, AgTech investors must develop stronger ties with farming communities, and align their strategies with the characteristics of the industry. Specifically, they need to adapt their time horizons to longer sales cycles in Agriculture, and often-lengthy paths to prototype and proof-of-concept development. While this extended timeline increases investor risk, it can translate into lower failure rates due to higher farmer adoption.

Second, AgTech investors need to partner with food businesses that have an expertise on the needs of growers, and are willing to be co-investors. Several food companies are already active on this front. Driscoll's invested in two robotic solutions for strawberry-picking: Harvest CROO and Agrobot, and has given them access to its fields in hopes of accelerating a scientific breakthrough [138]. Campbell's Soup has launched a $125 million venture capital project to invest in food startups [139]. Furthermore, there needs to be an increased diversification in the financial instruments made available to AgTech startups. The latter are often forced to rely on venture capital funding, or corporate M&A. Instruments such as debt, convertible bonds, or private equity funding would increase the sustainability of AgTech financing.

Additionally, there needs to a higher level of public support in agricultural research and development and the development of innovation clusters. As mentioned in 2.1.2, there has been a stall in governmental support of public agricultural research and development, especially in developed countries. This is perhaps best exemplified by the funding level of National Institute of Food and Agriculture (NIFA) in the US, the agricultural research arm of the USDA. In 2018, NIFA was awarded a $1.5 billion budget, out of which only $400 million were dedicated to research and education activities [140]. Although significant, this number seems limited in comparison to the $39.2 billion annual budget of the National Institutes of Health, the counterpart of NIFA at the Department of Health and Human Services [141]. Public agricultural research and development has plateaued in most developed countries, which is concerning given the magnitude of challenges facing Agriculture. There must be renewed public funding efforts if production and waste reduction goals are to be met.

4.2.3 The Israeli model

Israel has developed an interesting model for the creation of agricultural innovation ecosystems, which has produced numerous impactful ventures with international validation. Notably, Israel's AgTech sector has attracted $759 million in venture capital investments between 2014 and 2018 [142]. In 2017 alone, Israel raised more private investments for upstream technologies ($187 million) than China, and nearly as much as India over five years [143]. These investments have fueled an entrepreneurial ecosystem that comprised nearly 700 startups in 2018 [143]. Although funding levels seem limited in comparison to the $16.9 billion invested globally in AgTech in

2018, they have to be put into perspective. Israel has a population of less than 9 million people, and its geographic size is similar to that of New Jersey, thus highlighting the dynamism of its AgTech industry [143].

Several factors underpin this success. First, the founding teams of Israeli AgTech ventures often showcase a combination of farming background, education in world-class agronomic institutions, and experience with modern military-grade sensing and imagery technologies [142]. Most founders also grew up on a kibbutz (farming commune), where they have had exposure to farm-centric solutions, and have built a network that facilitates future field trials [142]. Second, there has been tremendous support from local and national government for agricultural innovation. Military-grade technologies in imagery and sensing have been repurposed for AgTech [142]. Public organizations, like Start-Up Nation Central have fostered innovation and helped startups attract investors [142]. Government, through the Israel Innovation Authority, has backed two of the most prominent Israeli AgTech investors: the Kitchen FoodTech Hub and the Trendlines Group [143]. Trendlines has been the most active investor in the sector, with 19 deals since its launch in 2007 [143]. This public support is perhaps best explained by the strategic importance of technology exports and Agriculture, in a country that suffers from a scarcity in natural resources. Benjamin Belldegrun, managing partner at Pontifax AgTech, interviewed by AgFunder in 2019, best summarizes Israel's success in AgTech. *Israel has been a dominant force in biotech and high tech and is now a significant presence in food and AgTech,* he said, attributing it to *university-led technological advancements, agronomic necessity, governmental support through capital infusion and growing strategic corporate representation.* This has led Israel to produce world-class farm technology, and cutting-edge startups that have received international validation. Namely, Prospera Technologies has developed computer vision solutions for indoor and outdoor farms to detect and identify crop stresses such as diseases and nutrient deficiencies [144]. Prospera raised a $15 million series B round in 2017, and one of its largest customers is Naturesweet Tomatoes, a US-based greenhouse grower of specialty tomatoes [144]. Its $7 million series A in 2016 was led by Qualcomm Ventures and Cisco, two global telecommunications companies [144]. CommonSense Robotics has raised $26 million over 5 years to accelerate the development of its automated micro-fulfillment technology [142]. CropX raised $10 million for its series A round in 2016, notably from Robert Bosch Venture Capital and Flextronics [145].

Overall, Israel represents a powerful template for agricultural innovation ecosystems, relying on a carefully designed mesh of government support, public funding, scientific research, access to farming communities and technology education.

4.3 Agriculture: become a collaborative industry platform

The whole Agriculture industry should become a collaborative *industry platform*. Industry platforms can be briefly defined as sectors that facilitate the generation of complementary innovations and provide technological foundation for innovative business ecosystems [146]. They can lead to tremendous benefits, as exemplified by the fast development of the Personal Computing (PC) industry in the 1990s, under the leadership of Intel. There are significant opportunities for collaboration in Agriculture, ranging from beta tester communities, to large-scale scientific research, and data cooperatives. However, Agriculture has often been plagued by a lack of cooperation, as highlighted by the recent right to repair movement, mentioned in 4.1.1.

4.3.1 Definition and benefits of *industry platforms*

In a 2014 article, Annabelle Gawer and Michael Cusumano defined industry platforms as follows: *products, services, or technologies developed by one or more firms which can serve as foundations, upon which a larger number of firms can build further complementary innovations and potentially generate network effects* [146]. There are several landmark examples of products or technologies that acted as industry platforms: Microsft Windows, Linux, Intel microprocessors, Apple's iPhone and App Store, Google's search engine, Facebook, and the Internet itself [146]. Industry platforms are born out of architectural design decisions, the intent of business leaders to establish mutually beneficial relationships with other industry participants, and their ability to develop profitable business models [146]. Industry platforms enhance the degree of innovation on complementary products and services [146]. The more innovation there is on complementary products, the more value it creates via network effects [146]. The concept of industry platforms is perhaps best illustrated by the development of the PC industry in the early

1990s. Frustrated by the limits of the PC platform technology, Gordon Moore and Andy Grove, Intel's chairman and CEO, decided to heavily invest in design architecture to move it ahead at a faster pace [146]. In 1991, Intel established the Intel Architecture Lab (IAL) to address the limitations of the PC platform technology [146]. IAL's mission was to become a *catalyst for innovation in the industry*, by creating new applications for computing devices and thus generate demand for new computers [146]. By 1997, IAL's mission became even broader: *to establish the technologies, standards and products necessary to grow demand for the extended PC through the creation of new computing experiences* [146]. These research and development efforts quickly accelerated the development of the entire PC industry, and simultaneously led Intel to become the leading manufacturer of microprocessors. This also allowed the development of numerous complementary innovations that are widely used today, notably software applications.

4.3.2 Opportunities for platform solutions in Agriculture

Platform products could bridge significant industrywide gaps that have hindered the development of agricultural innovations. Agribusiness firms, or AgTech startups should subsidize their development to enhance collaboration, and build the foundations of innovative ecosystems.

One hindrance to the development of compelling proof-of-concepts for agricultural innovations has been the absence of structures that support large-scale scientific research. Engaging producers in field trials is generally challenging, and AgTech startups can only pilot their technologies on small plots because of limited funds. Because of significant field or soil variability, trial results do not transfer well to other farms, and thus are often not convincing enough for farmers to make investments. There is a need for sponsored large-scale research to clearly prove the benefits of innovative technologies and accelerate their adoption on farmland. Indigo has been spearheading efforts on this front, through the launch of Indigo Research Partners in 2018 [126]. In under a year, Indigo has made 50,000 acres and 120 growers available for technology pilots through its network of customers [126]. This has allowed 100 ventures to pilot their technologies on farms across the US [126]. Such efforts can also contribute to creating a crucially needed community of beta testers in Agriculture. Through pilots, feedback and participation to product development, the community launched by Indigo might lead to solutions that better respond to the needs of growers, and scale more rapidly.

Another industrywide gap that has hampered the emergence of robust farm analytics solutions has been the absence of a central repository of farm data. Cooperatives, which have been longstanding structures in western Agriculture, should be extended to data storage and analysis. A farm data cooperative could increase the safety of data collected on farmland, enhance its value through aggregation, and allow entrepreneurs to build robust analytical models to optimize production. Farmers had expressed their desire for such a cooperative in a 2016 survey by the American Farm Bureau [96]. Since then, the American Farm Bureau has launched three initiatives: a data transparency evaluator, a cooperative data repository, and education programs to inform farmers and ranchers on data technology [96]. However, these efforts are insufficient and need to be supplemented by private initiatives. Two private ventures have been trying to move the industry in this direction. In 2018, IBM announced the extension of Watson services, an AI-powered analytics platform, to farm-based data [147]. Simultaneously, IBM asserted that these services should be powered by a data cooperative, which would protect farm records and run analytics on a combination of growers anonymously [147]. Similarly, the analytics offered by Farmers Business Networks are based on the aggregation of anonymized member data [65]. Farmers Business Networks claims that it allows farmers to obtain objective information on seeds, fertility, soils and analytics with higher transparency [65]. *Working together, [farmers] knew they could learn vastly more than by looking only at just their own farms, thereby unlocking the true power of the precision farm data they'd paid for*, mentioned their website in 2019 [65].

4.3.3 The common lack of collaboration in Agriculture

Transitioning Agriculture into a platform industry is especially crucial as it has often suffered from a lack of collaboration. This is perhaps best exemplified by the recent right to repair movement, mentioned in 4.1.1. The decision of farming equipment suppliers to lock their machinery to individual repairs has spurred intense criticism, and resulted into a protracted legal battle. Instead, suppliers should completely open their hardware and software, upon which innovative complementary applications could be integrated. Similarly, lack of collaboration in the prediction of supply and demand for food has caused significant food loss and waste, according to a 2018 BCG study [43]. To remedy this, the BCG proposes that producers, food processors and governments cooperate to develop more accurate supply and demand forecasting models [43]. To do this, public agencies could create a data cooperative to collect, aggregate and anonymize consumer demand forecasts from processors and retailers [43]. This consolidated data would then be shared with food producers for them to adjust production plans [43]. The BCG states that such initiatives in certain markets have allowed to cut overproduction to zero [43]. The shortcomings of Ocean Spray, the biggest cranberry cooperative in the US, to predict demand in recent years have highlighted the need for better demand forecasting. In the 1990s, Ocean Spray encouraged growers to invest in production growth based on too optimistic demand forecasts [148]. Ocean Spray even offered grants to subsidize production [148]. However, as sales stabilized a decade later, Ocean Spray had to implement volume control measures [148]. This led to the destruction of 15% of the American cranberry production in 2000, and 35% the following year [148]. This problem still persists today, as the cranberry industry collectively decided to destroy 25% of crops in 2018, to regulate volumes and maintain price levels.

Overall, Agriculture needs a firm willing to subsidize a platform product upon which complementary innovations could be built, as Intel did for the PC industry in the 1990s. Only then will it be sufficiently equipped to overcome the challenges it is currently facing.

4.4 Proposed concept for food waste reduction in agricultural production

The final part of this work proposes an early-stage solution to mitigate several of the factors that lead to food loss and waste in the fresh produce industry. This concept was developed in collaboration with classmate Helena Briones, through a systems design course taught by Professor Sang-Gook Kim at the Massachusetts Institute of Technology. Initially, a specific problem in fresh produce waste will be defined and analyzed. Then, the design of the solution will be described, along with an explanation of the process that led to it. Finally, the details of the solution, its potential impact, and risks to its success will be presented.

4.4.1 Problem definition

Fresh produce is the category that generates the most waste in the global food supply chain [43]. 46% of fruits and vegetables are wasted annually, or an equivalent of 644 million tons of crops, worth nearly $500 billion [43]. In developed countries, such as Europe, the US and industrialized

Asia, 52% of this waste occurs between the farm and its distributor (i.e during farming, post-harvest operations and food processing). Fresh produce was also of particular interest because of its short shelf-life, and large production value. Specifically, leafy greens have a 2-week shelf life, and represent over $3.2 billion in annual production, making it the largest vegetable market in the US [149,150].

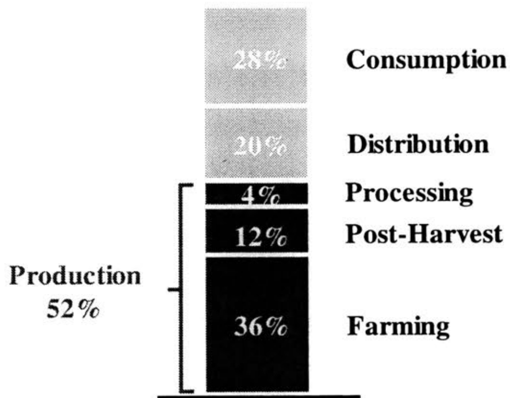

Figure 33. Contribution of each phase of the supply chain to fruit and vegetables waste. Data from [44] *averaged over the US, Europe and Industrialized Asia.*

Several factors mentioned in 2.4.2 underpin this situation, ranging from the lack of consumer awareness, supply chain inefficiencies, or the lack of appropriate public policies [43]. However, two particularly stood out as being conducive to waste during production phases: the concentration of the retail industry, and the lack of industrywide collaboration. As mentioned in 3.4.3, the top four grocery chains control 44% of the American food retail market [97]. This provides retailers with significant bargaining power over both supply and demand, and allows them to resort to supply control practices when needed. Additionally, the lack of industrywide collaboration on the prediction of supply and demand has often led farmers to overproduce, as exemplified by the case of Ocean Spray in the 2000s, described in 4.3.3. Figure 34 below presents a usual process flow between farmers, retailers and consumers.

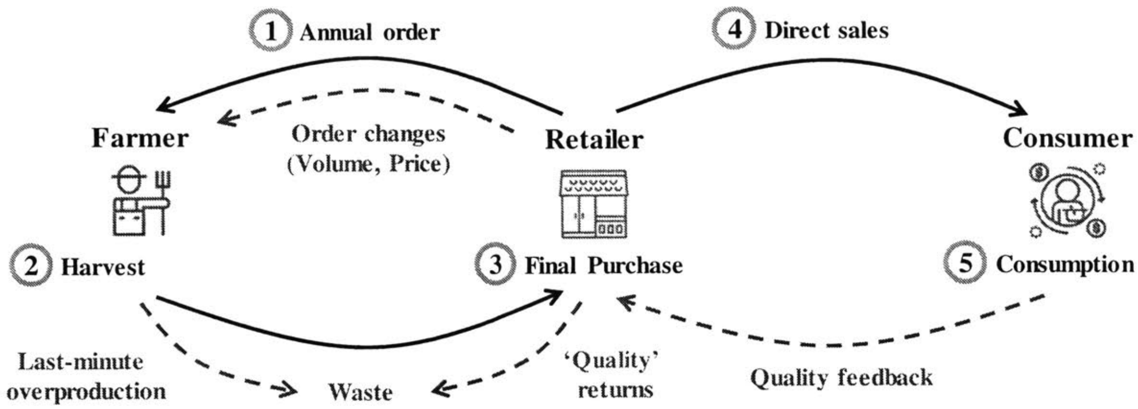

Figure 34. Process flow between farmers, retailers and consumers. In red, four sources of waste stemming from current industry practices. Derived from farmer interviews, industry reports and new articles. [151].

To ensure that their demand will be met, retailers generally make yearly orders to growers, based on their market projections. To hedge their operations, growers tend to overproduce by 7% to compensate for fluctuations in wholesale orders, weather events and diseases [109]. However, retailers often change order volumes, leaving growers with an excess of produce at harvest that is difficult to sell because of limited marketing capabilities. In addition, retailers often return produce based on quality standards that growers dispute [108]. Furthermore, because of the absence of accurate yield forecasting models, excess production increases at harvest, when farmers realize that their crop yielded more than expected. This leaves them with even more produce for which they have to find a customer in a timely manner. Conversely, retailers are generally unable to trace food from farm to fork. This can lead to disease outbreaks, and trigger recalls and tremendous waste that can hurt entire sectors, as exemplified by the recent E. Coli outbreaks in lettuce [152]. This puts pressure on retailers, and can be detrimental to both farmers and consumers.

This situation is perhaps more easily understood by presenting what farmers, retailers and consumers control, do not control, and are looking to improve, respectively:

1. **Growers**:
    a. <u>Control</u>: production and planting decisions
    b. <u>Lack of control</u>: yields, access to customers, negotiations with retailers
    c. <u>Needs</u>: profit improvements through differentiation or cost reduction, stable revenue
2. **Retailers**:

a. Control: supply contracts, quality standards, consumer supply
b. Lack of control: quality control, traceability from farm to fork
c. Needs: market share increases and profit maximization, reduced liability

3. **Consumers**:
   a. Control: purchasing decisions
   b. Lack of control: supply, quality control
   c. Needs: diversity of food supply, lower prices, reduction of disease outbreaks

Based on these, three gaps were identified, listed below:

1. Farmers cannot accurately forecast yields before harvest, leaving them with excess production.
2. The food supply chain lacks universal quality control combined with traceability from farm to fork.
3. Farmers do not have access to a time-efficient and cost-effective way to acquire new customers, which makes them dependent on retailers.

These three gaps are conducive to waste in different ways, respectively:

1. Last-minute waste due to overproduction that farmers are unable to sell in a limited amount of time.
2. Disease outbreaks leading to wide-ranging product recalls.
3. Overproduction due to supply control practices, notably product returns and order fluctuations.

4.4.2 Solution design

Because of how intricately related the three gaps mentioned above are, a holistic solution to address them all simultaneously was preferred. As a result, the proposed concept comprises three components: a yield forecasting tool to help farmers anticipate production and marketing efforts; the preservation of farmer identity from farm to fork coupled with universal quality control; an online marketplace to directly connect growers with retailers or consumers.

Initially, three concepts were considered:

1. **Technology platform**: A set of technology tools, including yield forecasting, universal quality control and preservation of farmer identity, and an online marketplace to directly connect growers with demand.
2. **Agricultural cooperatives**: An association of farmers that negotiates contracts with retailers; forecasts market supply and demand through the aggregation of farm data, and guarantees quality control and traceability.
3. **Agricultural policies**: A set of policies ranging from farm subsidies to invest in forecasting solutions, food waste reduction incentives, and public quality standards for fresh produce.

To evaluate them and guide a more detailed design of the preferred one, a set of functional requirements (FR) and associated design parameters was developed, both of which are listed in Table 21 below. To incorporate the tight financial situations of farmers into the solution design, a constraint was added to the set of functional requirements: low cost to the user, through a fixed annual fee.

Table 21. Functional requirements, design parameters and constraints for proposed solution.

#	Functional Requirement	Design Parameter
1	**The system accurately predicts production levels before harvesting**	
1.1	Predicts farm production levels	Accuracy (> 95%)
1.2	Provides farmers with enough time to plan sales and marketing efforts	Time to harvest (> 30 days)
1.3	Updates prediction levels in near real-time during growing	Prediction frequency (2/month)
2	**The system traces produce through the supply chain with a controlled quality**	
2.1	Tracks produce through the food supply chain	Record of production, alteration and transportation
2.2	Preserves farmer identity	Certification of farm origin
2.3	Provides information on produce characteristics	Safety standards, variety, nutritional values, quantity (tons)
3	**The system provides a fast and cost-effective way for suppliers to connect with demand**	
3.1	Accelerates customer acquisition for farmers	Customer acquisition time (< 4 weeks)
3.2	Decreases cost of customer acquisition	Cost of Customer Acquisition ($/customer)
3.3	Accelerates produce transactions	Time per transaction (number of days)
#	**Constraint**	**Constraint requirement**
1	**Low cost to the user**	Fixed annual fee; $/year

Several of these design parameters are yet to be defined with higher granularity (e.g. cost of customer acquisition, time per transaction, certification of farm origin). This will be a pivotal part of the necessary future work on this proposal.

An evaluation of the three proposed concepts was conducted, based on assessments of their likelihood to meet the three primary functional requirements (FR.1, FR.2 and FR.3). Figure 35 below shows the result of this evaluation, which led to the selection of the technology platform.

	TECHNOLOGY PLATFORM	PRODUCTION COOPERATIVES	GOVERNMENT POLICIES
FR.1			
FR.2			
FR.3			
CONSTRAINT: Cost			

Figure 35. Evaluation of the three proposed concepts against primary functional requirements.

Through farm data aggregation, a cooperative would be able to predict crop yields on a large scale. However, these predictions would be based on historical data with a reduced accuracy compared to near real-time technological solutions, namely satellite-based imagery. Cooperatives could also predict demand through information exchange with retailers. However, such information exchange has often led to deficient projections, as exemplified by the case of Ocean Spray. Market-based solutions, such as online marketplaces, would provide the industry with demand data of higher reliability and transparency. Finally, although cooperatives could implement traceability solutions across their members, their adoption would be subject to the approval of other stakeholders, an unlikely outcome given that cooperatives are farmer-owned. Solutions provided by independent third parties, such as tagging systems or blockchain technologies, could lead to a higher engagement of the entire industry. Even though farm subsidies could support farming profits, they do not seem like a sustainable solution as opposed to marketplaces or cooperatives that can increase the bargaining power of growers over the rest of the industry.

A similar evaluation process was conducted to select the physical components of the proposed solution. For each primary functional requirement, a range of technologies was analyzed before selecting the option that seemed the most promising. Figure 36 below displays the results of an evaluation for yield forecasting solutions, which led to the selection of satellite-based imagery.

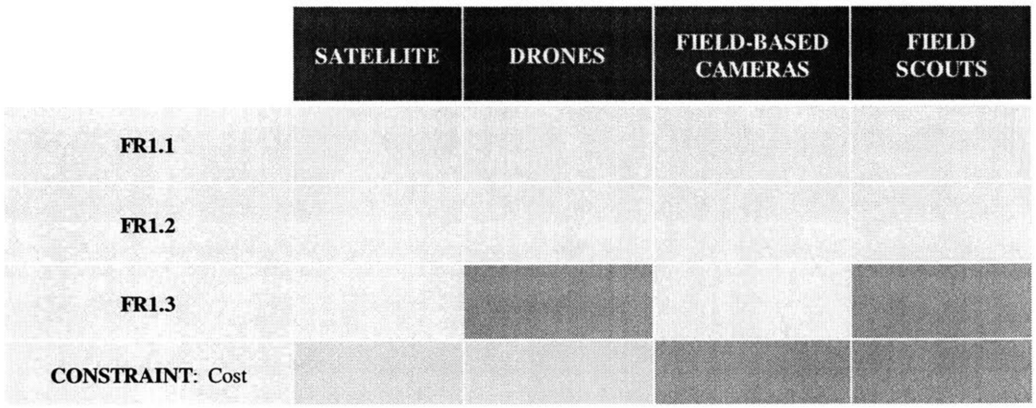

Figure 36. Evaluation of four proposed technologies to meet FR.1.

Satellite-based imagery was selected for this physical component. While drones can generate high-resolution imagery of fields, they have a limited range, and require costly manpower. Similarly, field-based cameras, while being a promising solution, were too costly on a per acre basis as compared to satellite-based imagery. The other two physical components of the proposed solution were selected via a similar process.

4.4.3 Solution details, risks and potential impact

Overall, the proposed solution would leverage the following three technologies on a platform made available to all stakeholders (Figure 37 below presents a high-level systems diagram):

1. **Satellite-based yield forecasting**: crop production levels are estimated through the analysis of satellite measurements: field images, surface and subsurface temperatures, and moisture contents. Farm results are communicated bi-monthly to farmers during the growing season to anticipate sales levels and optimize commercial efforts. Global production levels are communicated to food processors and retailers in preparation of orders.
2. **Laboratory-grade tests for safety and quality metrics; farmer identity preservation through unique, food-safe chemical tags**: A sample of produce is sent to a network of partner laboratories for analysis. Results on safety levels, nutritional levels and quality are engraved after cleaning or processing, in food-safe chemical tags applied on produce.

3. **Online marketplace to directly match supply and demand for fresh produce**: Growers list produce and expected quantities during the growing season. Specific quality and safety data is automatically uploaded after the completion of tests. Growers then receive bids from retailers or consumers for produce. Anonymized, aggregated transaction data is analyzed, and results are made available to all stakeholders for demand prediction or further analysis.

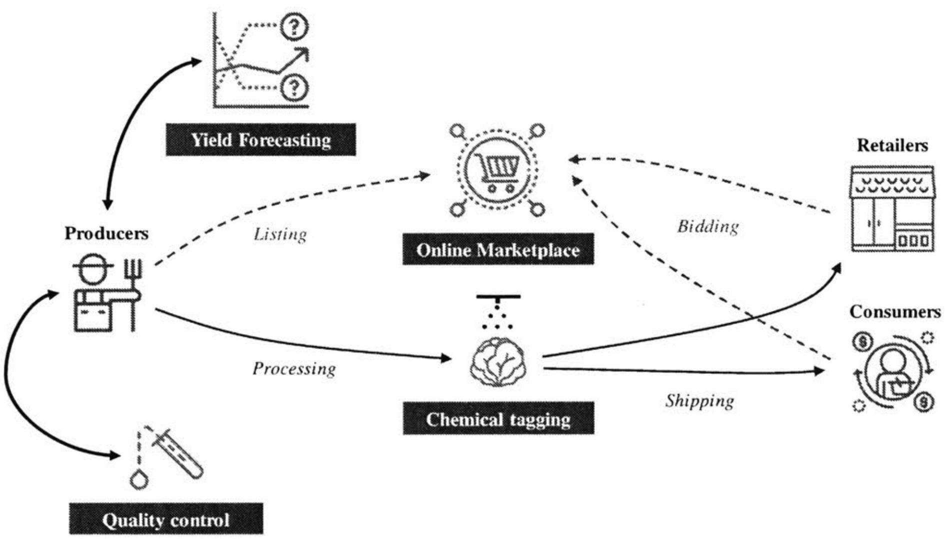

Figure 37. High-level systems diagram of proposed concept. [151].

These three solution components present significant risks. The main risk for the proposed yield forecasting solution would be to fail predicting farm production levels with sufficient accuracy. Companies like Descartes Labs have developed algorithms that led them to predict national yield levels in the US and outperform USDA projections [153]. However, these models have yet to translate to individual farms with equal success. The riskiest component of the proposed solution is perhaps the preservation of farmer identity through chemical tags. The main risk there would be the failure to implement fast enough processes for testing, tagging and data communication, especially in a sector where products have limited shelf-life. Another key risk would be excessive cost to stakeholders because of the large investments needed to deploy testing and tagging equipment. Although still risky, the technical feasibility of this component has been demonstrated by startup Safe Traces, which develops food-safe, DNA-based tagging material [154]. The least risky component of the proposed solution is the online marketplace. Such services have already been developed in multiple other industries, and notably, the Indigo Marketplace has received significant validation from the Agriculture industry [126].

Although highly risky, the proposed solution could have significant impact, should it be successful and widely adopted. Through faster, more transparent market access, and more accurate production plans, farmers would reduce the amount of produce that ends in landfills, and turn it into additional revenue. Furthermore, they would benefit from an enhanced brand image through quality control and preservation of farmer identity. As a result, it would be easier for them to meet their demand more effectively, and unlock premiums through differentiation. Finally, being able to predict fluctuations in supply and demand would allow them to refine production plans and planting decisions. Through the online marketplace, retailers would have an easier access to produce that match the needs of their consumers, and increase customer satisfaction. Through quality control and preservation of farmer identity, they would face a reduced risk of disease outbreaks and industrywide product recalls. Similarly, consumers would benefit from a reduced risk of contamination, as well as access to a higher diversity of foods that meets their demands.

Overall, future work will be needed to reduce the risks associated with the proposed solution components. Critical farmer feedback, experimentations and prototyping will help refine the understanding of risk factors, as well as move the development of this proposal ahead. A list of such efforts will be presented in the conclusion of this work.

5 Conclusion

Overall, AgTech has put forward a wide range of novel options to help Agriculture overcome many of the challenges it is currently facing. The realization of these options, however, will be subject to considerable changes in the global food system. First, AgTech ventures must primarily focus on value creation for food producers, and present sufficient incentives for them to incur the risk of investing in them. Second, innovative ecosystems must be developed to accelerate the development and adoption of novel technologies on farmland. Third and most importantly, there must be increased collaboration between all stakeholders of the global food industry, be they retailers, food processors, consumers, entrepreneurs and governments. In parallel, a disruption of industry paradigms must take place, along with increased awareness of food production challenges and food waste and loss. Finally, these changes must be catalyzed by a renewed and adequate governmental support, for demand to be sustainably met, and for food waste reduction goals not to remain smokescreens. Only then will there be enough elements to transition Agriculture towards a crucially needed sustainable intensification.

5.1 Future Work

One of the primary areas of future work will be the communication of this work to communities of agricultural research and entrepreneurship engaged during the development of this thesis. This will enable the collection of critical feedback to refine the recommendations proposed in 4, and hopefully lead to a broader communication that proposes their implementation, in collaboration with research institutions.

Parts of the evaluation of the impact of AgTech, and the analysis of the factors underlying its limitations have been derived from qualitative reports, interviews and quotes from industry experts. This evaluation could be expanded greatly, notably via the conduction of a survey in global agricultural communities to refine and quantify these insights.

The recommendations mentioned in 4 could also be expanded to be more easily exploitable by interested stakeholders. Specifically, a more detailed roadmap could be created for the development of clusters for agricultural innovation proposed in 4.2.1. Additionally, system designs could be elaborated for the platform products mentioned in 4.3.2. Similarly, the design of tools to monitor and track the quantities of food waste and loss, currently nonexistent as mentioned in 3.4, could be proposed.

Finally, the concept proposed in 4.4 is still in its early stages. Critical farmer feedback, and user interviews will be needed to refine the design parameters presented in 4.4.2. Testing of the proposed solution components will be needed to refine the understanding of risk factors, and reduce the risks associated with their development. Specifically, tests on publicly available satellite imagery in collaboration with farmers, powered by open-source algorithms would lead to a clearer assessment of the feasibility of yield forecasting based on satellite imagery. Testing of the Safe Traces technology on fresh produce would help refine the quantification of costs associated with its implementation, and the feasibility of its deployment in the overall food supply chain. The development of a matchmaking service between produce growers, retailers and consumers would provide valuable information on future market adoption of an online marketplace. It would also lead to the creation of a community of early adopters that would be critical in the development of a full-scale product. Following testing, a development roadmap should be proposed, as well as funding plans to support the creation of the proposed technology platform.

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