Potentials of GHG emission reductions from cold chain systems: case studies of China and the United States

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Abstract:

This study examines the trade-offs between energy consumption and food loss during the expansion of the cold chain from the perspective of carbon emissions. A nonlinear optimization framework is constructed to determine the optimal scale of the cold chain under the constant final demand and to analyze the potentials in GHG emission reduction for developed and developing countries using system dynamics. Meat, milk and aquatic products in China and US are selected as case studies. Results reveal that the expansion of the cold chain contributes to the reduction of total carbon emissions that 51.93%/29.34%, 3.16%/14.01%, and 84.17%/79.75% of current level of carbon emissions can be reduced from meat, milk and aquatic products in China/US, respectively, if the full coverage of cold chain could be acquired at the current level of final food demand. Meanwhile, the efficiency of the "trade-offs" varies from food categories to countries, that averagely each increased unit (in CO_2e) of electricity will avoid 3.34/5.94, 1.06/1.43 and 19.85/16.14 unit (in CO_2e) of food loss for meat, milk and aquatic products, respectively. Diet structure, power generation structure and carbon footprints of food products and electricity are all contributing to the differences of the trade-offs between the increased energy consumption and the avoided food loss by cold chain.

Keywords:

Cold chain, food loss, GHG emission, trade-offs, system dynamics

Nomenclature list

L	energy consumption related to use of refrigeration
$K(t)$	food amount within cold chain at time spot t
K_{loss}	carbon investment related to the production of the lost food
$K(t_{final})$	final food output of cold chain system
$demand$	final food demand
$foodloss(t)$	food loss within cold chain at time spot t
ρ	contamination rate of per unit of bacteria
$N(t)$	population of bacteria within food at time spot t
P	edible amount threshold of food item
r	intrinsic growth rate of bacteria
C, D	constant coefficients
ω_i	scale rate of the cold chain of group i

T_i	ambient temperature within cold chain of group i
t_i	deliver time in group i
$power_i$	power of refrigeration facilities in group i
M	total scale of food system.
M_i	scale of food system in group i

1. Introduction

The cold chain is a refrigerated supply chain that maintains desired low-temperature for production, storage and distribution of merchandise. In the food supply system, the cold chain has the potential to maintain food safety and reduce food loss, which contributes to human well-being improvement. While in most industrialized food systems like Canada (Mercier, S., et al.,2018), France (Derens-Bertheau, E., et al., 2015) and New Zealand (Carson, J.K. and East, A.R., 2018), the cold chain has been defined as an essential element, the installation of cold chain in food systems in emerging economies is still at low level. According to China Cold Chain Logistics Development Report[1], the overall coverage rate of cold chain in China in 2015 is merely 19% compared with an average of over 95% in Europe and US. Less than 25% of meat products and 5% of fruits and vegetables along the supply chains are stored with refrigeration in China, causing approximately 12 million tons of fruits, 130 million tons of vegetables, and 6.9 million tons of meat spoilage. These food losses represent more than 100 billion CNY economic losses and 7 million hectares of cultivated land, not accounting for the embodied emissions associated with producing food that is not consumed (Zhao, H., et al., 2018). An estimation from International Institute of Refrigeration (IIR, 2009) suggests that over 200 million tons of perishable foods, accounting for 14% of total production, could be saved every year if developing countries could acquire the same level of refrigerated supply chain as industrialized countries (Parfitt, J., et al., 2010). Meanwhile, food loss is causing about 3.3 billion tons of CO_2 equivalent, ranking as the third GHG emitter globally if it were a country, after the US and China (Rezaei, M., et al., 2017). The extent of the problem indicates the critical role of cold chain in both reducing food loss and controlling carbon emissions, which are associated with the Target 12.3 and 13 of Sustainable Development Goals (SDGs).

Food loss is defined as edible food at one stage that is not supplied to the next stage along the supply chain (Gustavsson et al., 2011). 30%-40% of total food production in developing countries are reported lost and wasted along the supply chain every year (Wakeford, J., et al., 2015). During the past decades, increasing literatures have highlighted the benefits of promoting refrigerated food supply chains and ensuring adequate cold chain for food products in developing countries (Kitinoja, L., et al., 2013). Researches reveal that the increased installation of cold chain will have positive impacts on combating hunger literatures (Winkworth, C., et al., 2015) , improving community health (Goransson, M., et al., 2018), raising rural income (Wu, P.J. and Huang, P.C., 2018) and reducing land waste (Liu, J., et al., 2013) and other natural resources waste (Arias Bustos, C. and Moors, E., 2018). However, the use of refrigeration also causes energy consumption and refrigerant leakage, which are major contributors to climate change (Garnett, T., 2011). The existing cold chain is responsible for approximately 1% of global GHG emissions, and can represent 3-3.5% GHG emissions in developed economies such as UK (Heard, B. and Miller, S., 2018). Meanwhile, the vast and growing demands for fresh foods in emerging food

[1] Cold Chain Logistics Committee of CFLP. China Cold Chain Logistics Development Report (2018)[R]. China Fortune Press. 2018.

systems have motivated the rapid development of cold chain system in developing countries (Kazancoglu, Y., et al., 2018). The increase of carbon emissions and burden on environment due to the use of cold chain from developing countries highlights an important tradeoff for this technology (Adekomaya, O. et al., 2016).

Despite the increasing concern on the development of cold chain, limited empirical studies investigated on the tradeoffs between energy consumption and food loss during the expansion of the cold chain. Global Food Cold Chain Council (GFCC, 2015) detailed the potential of the cold chain sector to reduce GHG emissions through food loss and waste reduction, and highlighted the role of cold chain sector in GHG emission reduction. Hoang et al. (2016) conducted a life cycle comparison of different technology in salmon cold chain of food loss and energy efficiency. Heard and Miller (2018) used sub-Saharan African as a case study to compare and discuss the potential changes of GHG from cold chain in developing food systems if the North American and European level of cold chain could be acquired. These studies discussed the connections between the introduction of cold chain and the associated GHG emissions changes, and concluded the positive impacts of cold chain in reduction of total GHG emissions from a general level. However, the relationships between the increased energy consumption and the reduced food loss, and what is the mechanism behind this are not fully revealed. Meanwhile, besides highlighting the positive effects of expansion of cold chain for human's general well-beings, this paper tries to find out how and how much, under specific contexts, cold chain can contribute to the GHG emission reductions by avoiding food loss along the supply chain. We examine the relationships between food loss and energy consumption during the expansion of cold chain, and intend to determine the potentials of GHG emissions changes of cold chain for developed and developing countries under the current technique level. A system dynamics model incorporates microbial populations, temperature, time, food category, food loss and energy consumption is promoted to simulate the trade-offs between food loss and energy consumption due to the use of cold chain. A nonlinear optimization framework is applied to determine the minimum total environmental impacts of cold chain, under the assumption of the constant food demand, diet structure, energy structure and the same efficiency of refrigeration equipment between developing and developed countries. China and the US are selected as case studies to analyze and compare from specific food categories under the current technology penetration level, to determine and identify the differences in potentials of GHG emission reduction with the development of cold chain.

2. Materials and methods

The cold chain can be regarded as a transformative technology that transfers the carbon investment from food production to refrigeration, resulting in food loss decrease and energy use increase. As is noticed along the food's life cycle that the production/preharvest process constitutes 50-90% of direct emissions, while the postharvest process (like processing, refrigeration and transportation) contributes to the major indirect emissions(Porter et al., 2016), it is necessary to analyze the tradeoffs associated with the decreased carbon emissions from the avoided food loss and the increased carbon emissions from energy use of refrigeration, and to find out how to minimize the total carbon emissions from the food system level. This study uses a non-linear optimization framework to determine optimal cold chain deployment in order to provide insights on how cold chain systems might best evolve to provide optimal quality and quantity while minimizing GHG emissions for both developed and developing countries.

In this analysis, the carbon emissions associated with the cold chain is accounted from two sources: energy consumption related to the use of refrigeration (L) and carbon investment related to the production of the lost food (K_{loss}). Thus, a basic framework is proposed here to represent the total carbon emissions:

$$min\ \tau L + \sigma K_{loss}$$

Where τ and σ are coefficients for carbon emissions of energy consumption and food production, respectively. Meanwhile, the food demand is restricted as:

$$s.t.\ K(t_{final}) \geq demand$$

$K(t_{final})$ is the final food output of cold chain system, which is supposed to satisfy the food demand.

2.1 Microbiological spoilage of foods

According to James and James (2010), food loss occurs as the results of microbiological (metabolism of microorganism), physical (water loss), or biochemical (e.g. browning reactions, lipid oxidation and pigment degradation) changes when proper preservation is absent. Among these changes, the metabolism of bacteria can be effectively controlled by lowering the ambient temperature of food products using refrigeration so that food spoilage can be prevented or alleviated. In this paper, food loss due to the metabolism of microorganism is emphasized with the association of cold chain. To reveal the relationships between food loss and energy consumption within a cold chain system, a system dynamic framework is proposed to illustrate the mechanism among food amount $K(t)$ with time t and energy L.

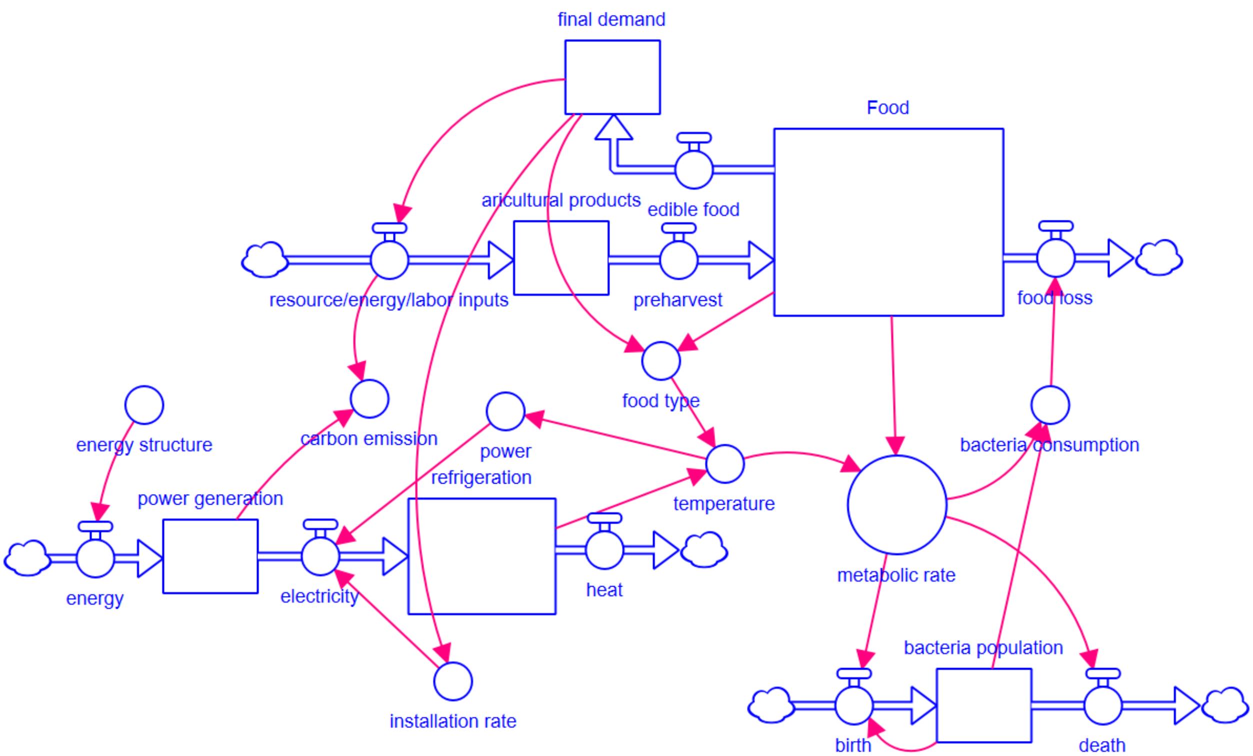

Figure 1 System dynamics of food loss and energy consumption

In Fig. 1, the food amount K is affected by the activity of bacteria within the food (water loss and other physical/chemical changes are not considered in this analysis). This activity is determined by the metabolic rate and population of microorganism. Meanwhile, a continuous energy consuming process is taking place due to the use of refrigeration facilities to control the temperature, which affects the metabolism of bacteria.

The kinetic model of this paper is based on Nychas and Panagou (2011)'s assessment of microbiological shelf life of food that food spoilage is closely relevant to the metabolism rate and population of the microorganism within food products. Thus, the dynamics of food with time $K(t)$ can represented as:

$$K(t) = K - foodloss(t) = K - \rho \times \int N(t)\, dt$$

Where ρ is the contamination rate of per unit of bacteria and is subjective to the ambient temperature of food products; $N(t)$ is the population of bacteria within food at time spot t.

Meanwhile, Amezquita et al. (2011)'s research suggests that despite the differences among various bacteria group within the food products, the primary growth model of microorganism for food spoilage and shelf life is a Logistic model, which is:

$$\frac{dN}{dt} = rN(\frac{P-N}{P})$$

Where $\frac{dN}{dt}$ indicates the increase rate of bacteria population N, and is also affected by bacteria's intrinsic growth rate r, current level of population N and the maximum population P. P represents the edible amount threshold of the food item and also indicates a certain bacteria population level. That is, the food product is edible and safe only when the population of bacteria within the food item is under a certain level. According to Mizrahi et al. (2011)'s description, the increase rate $\frac{dN}{dt}$ has a peak before which the increase of total population N dominates the rate, and after which the decrease of available food dominates the rate. Thus, the dynamics of food amount with time $K(t)$ can be determined:

$$K(t) = K - \frac{K}{r} \times \ln(Ce^{rt} - 1) + D$$

Where C and D are constant coefficients, and vary with specific food categories.

2.2 Energy consumption of refrigeration

The contribution of cold chain in extending food's shelf life is that a temperature-controlled environment can be provided for food processing, storage and distribution along the whole supply chain, so that the microbiological metabolism can be controlled under a safe standard. Meanwhile, energy is inevitably consumed during this period. Despite that the effectiveness and efficiency of cold chain depend on a range of factors including (physical, chemical and biological) characteristics of the food product, performances of the refrigeration facility, management measures, and the delivery time etc., which are further reflected in the environmental impacts, this paper focus on an overall estimation of total GHG emissions of food systems. Thus, it is reasonable to use the general parameters in this analysis.

From the macro level of food system, final food output is composed of a set of groups with different storage temperature. Temperature is used as the key factor to distinguish these groups that

$$K(t) = \sum_{i=1}^{n} \omega_i K_i(t_i) = \sum_{i=1}^{n} \omega_i \left(K - \frac{K}{r(T_i)} \times \ln\left(Ce^{r(T_i)t_i} - 1\right) - D \right)$$

$$\sum_{i=1}^{n} \omega_i = 1, \;\; i = 1,2, \dots, n$$

ω_i is the scale rate of the cold chain with temperature T_i, $K_i(t_i)$ represents amount of food in group i delivered with time t_i.

The energy consuming function for different period of refrigeration is different, considering chilling (lower the ambient temperature) costs more energy while freezing(maintain the temperature) costs relatively less. However considering the freezing period occupies the main period of cold chain at a fixed temperature and displays a linear relationship with food amount in a given time period, it is reasonable to describe the energy consumption for refrigeration as:

$$\frac{dL_i}{dt} = N_i \times power_i \times K_i(t_i)$$

Where L_i and $power_i$ represents total energy consumption and refrigeration power in group i. N_i indicates the scale of group i and $N_i = \omega_i N$, N is the total scale of the food system.

Hence, a connection between input ratio of food and energy can be built, that

$$L_i = N_i \times power_i \times \int K_i(t_i)dt$$

And

$$L = \sum_{i=1}^{n} \omega_i L_i$$

Equations above formulated the detailed quantitative relationships between food loss and energy consumptions. However, besides evaluating the food loss and energy consumption within the food system, it is necessary to build a unified framework under which these the trade-offs between food and energy could be comparable. As such, the carbon footprint is used in this paper to represent the GHG emission of food production or energy, to determine whether the energy consumption due to the use of refrigeration will compensate or even outbalance those from the production of the reduced food loss. As the objective function $min\ \tau L + \sigma K_{loss}$ contains parameters τ and σ, it is reasonable to use carbon footprints of food products and energy to determine the scale of cold chain from the GHG emission perspective. This indicates the minimum carbon emissions from the food loss and the energy consumption due to the use of cold chain.

2.3 Assumptions and data

In this paper, three food categories (meat, milk and aquatic products) are compared between China and US, the world's top two largest food systems, and to assess the potentials of GHG emission reduction through the expansion of cold chain. Differences in diet structure and current conditions of cold chain between China and US are included in this analysis. Two assumptions are made as follows:

(1) Refrigeration facilities are assumed to have similar performance in China and US.

This is reasonable because expanding the scale of cold chain mainly refers to installing more new equipment and replacing the old ones, rather than simply scaling up at the current cold chain status. Thus, either in China or US, these newly installed facilities are assumed to use similar advanced technology with similar performances. Besides, those performance gaps between the existing installations are expected to be diminished during the replacement and updates of facilities. Meanwhile, considering that refrigeration facilities' performances vary from brands, types, models, users' habits and local policies, power of refrigeration equipment[2] and coverage of cold chain are used as main parameters in this paper.

Besides, the contribution to global warming from the refrigerant leakage is not precisely accounted here due to the huge volatility from 6% to 28% (depending on the type of system, facility and refrigerant) of the indirect emissions from energy consumption according to EPA's report[3]. Therefore, the GHG emissions from the cold chain in this paper are mainly calculated through the consumption of electricity. Other emission sources, including the manufacture of cold chain and the leakage of refrigerant, are not accounted in this paper.

(2) Food products are categorized by raw material, regardless of the ingredients or processes.

Considering the giant differences of dietary culture between China and US, the various ingredients and processes in raw or processed food products make the precise GHG emissions tracking almost impossible. Additionally, the diversity of food products also determines the infeasibility of tracing their GHG emissions by product. However, given that food loss mainly happen in unprocessed procedure and preservatives are broadly used in industrialized food system, it is reasonable to categorize food products by raw material, despite that this may underestimate the results. On the other hand, this paper does include the diet structure differences between the two countries. For example, beef, pork, poultry and mutton are making different portions in meat category between China and US.

This diet structure along with the final food demand are assumed to be constant in the short term in this paper.

Data used in this paper is extracted from a series of public sources. Food related data is from China Statistics Yearbook 2018[4], USDA[5] and FAOSTAT[6]; Cold chain related data is from China Cold Chain

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[2] Refrigeration power data sources: Energy star [OL] https://www.energystar.gov

[3] The Institute of Refrigeration. REAL Zero-Reducing refrigerant emissions & leakage –feedback from the IOR Project[OL] https://www.epa.gov/sites/production/files/documents/IOR_ReducingRefrigerantEmissions.pdf

[4] China Statistical Yearbook[OL] http://www.stats.gov.cn/tjsj/ndsj/2018/indexeh.htm

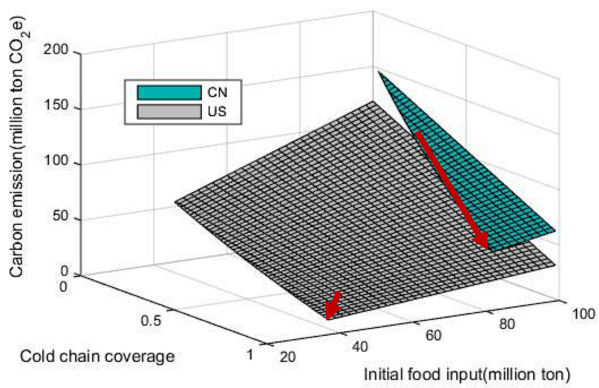
[5] USDA[OL] https://www.usda.gov/topcs/data

[6] FAOSTAT[OL] http://www.fao.org/faostat/en/#data. Food and Agriculture Organization of the United Nations.

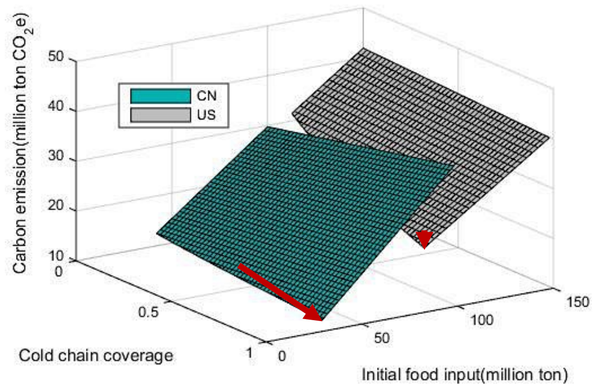
Logistics Development Report 2018[7], Statista[8], USDA[3] and Energy Star[2]; Carbon footprint related data is from EWG[9], USDA[10] and CSS[11].

3. Results

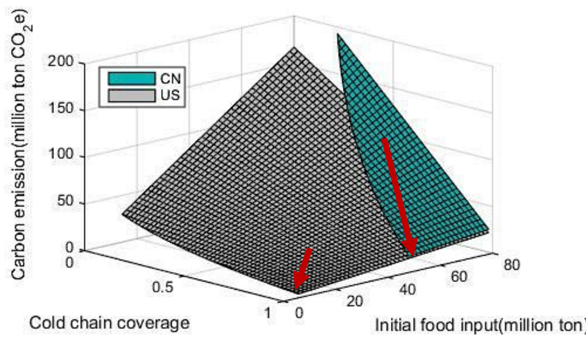
Fig. 2 illustrates the simulations of total carbon emissions from the three investigated foods categories under different combinations of cold chain coverage and initial food inputs along the whole supply chain at a given final demand. Red arrows highlight the directions and distances from the cold chains' current status in China and US to their potentially optimal status respectively.



(a) Meat



(b) Milk



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[8] Cold Chain Logistics[OL]. Statista. https://www.statista.com/study/48257/cold-chain-logistics/
[9] Environmental Working Group. Meat Eater's Guide to Climate Change + Health[R]. http://static.ewg.org/reports/2011/meateaters/pdf/methodology_ewg_meat_eaters_guide_to_health_and_climate_2011.pdf
[10] USDA Food Data Central[OL] https://fdc.nal.usda.gov/index.html
[11] Carbon footprint Factsheet 2018[OL]. Center for Sustainable System, University of Michigan. http://css.umich.edu/factsheets/carbon-footprint-factsheet

(c) Aquatic products

Figure 2 Optimization paths of cold chain in CN and US

In Fig. 2, the x-axis indicates the cold chain coverage(from 0 to 100%), the y-axis indicates the initial food inputs into the cold chain system, and the z-axis indicates the total GHG emission from both initial food production and energy consumption from refrigeration. In meat and aquatic products, the total GHG emissions of China are higher than that of US at the same x-axis and y-axis coordinates because of the huge demands and population in China. However, the conditions reverse in milk category due to the averagely low milk consumption level in China compared with that in US.

In all food categories between the two countries, the optimums, at which has the least total carbon emissions and satisfies the final demand, occurs at the edge of each surface in Fig. 2a,b,c with the full cold chain coverage. This reveals that for both China and US, full coverage of cold chain are beneficial for GHG emission reduction from the overall perspective. Thus, there are still potentials for GHG emission reduction by expanding the cold chain scale, regardless of the current level of refrigeration installation in US cold chain systems. It is also noticed in Fig. 2 that the length of red arrows, representing the distance from the cold chain's current positions to the optimal points in the two countries, indicate the potentials of GHG emission reduction in all categories. The longer the arrows are, the more potentials of carbon emissions for the cold chain. With no doubt that China has generally much larger potentials of GHG emission reduction through expanding the cold chain coverage.

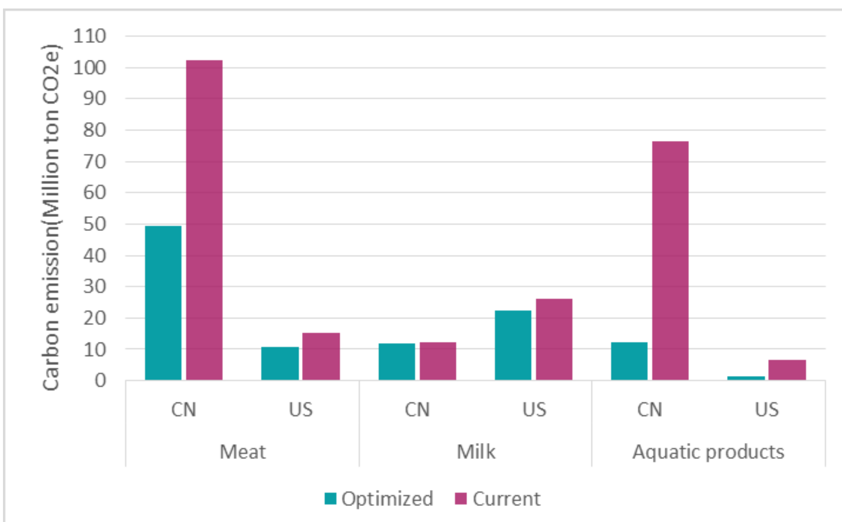
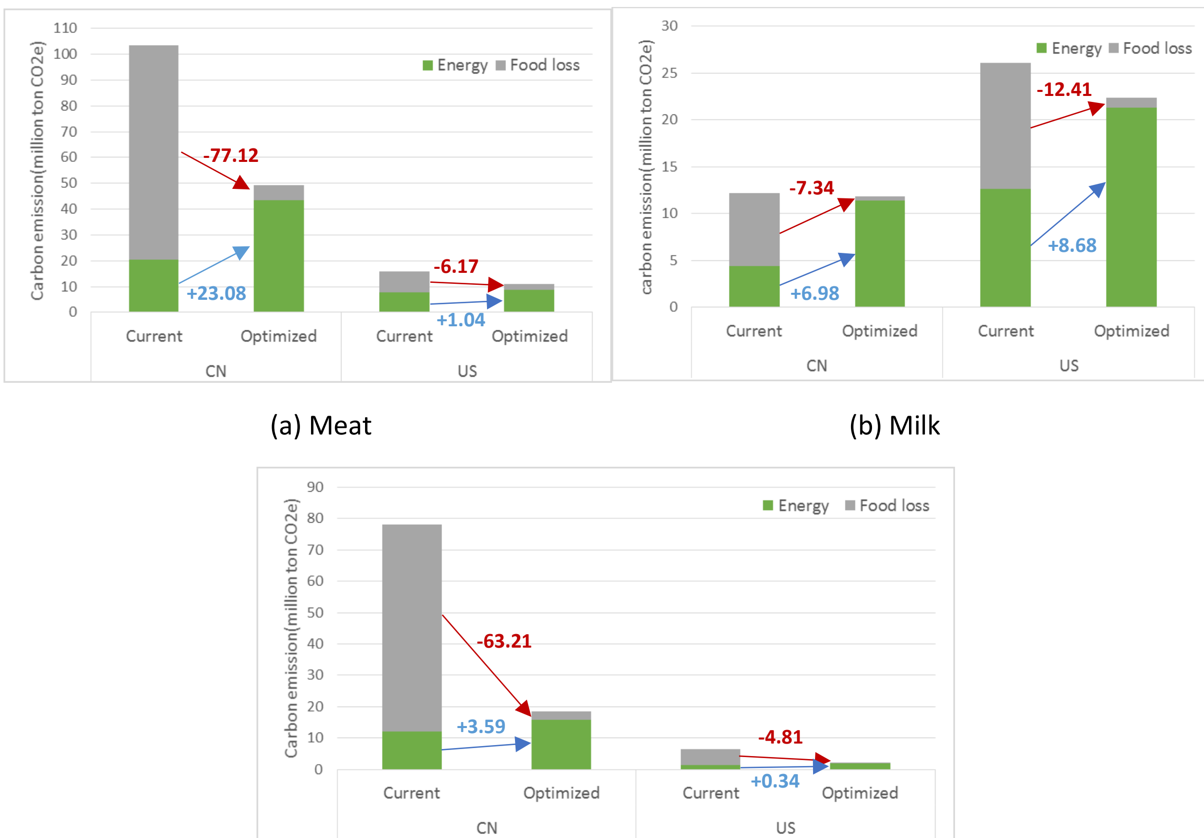


Figure 3 Total GHG emission (food loss and electricity consumption of cold chain)

Fig. 3 illustrates the potentials of overall GHG emission reduction for food system if the full coverage cold chain could be acquired for both countries in the investigated food categories. Obvious improvements are found in meat and aquatic products categories in China by the absolute values, that approximately 53.21 and 64.41 million ton CO_2 equivalent could be avoided through expanding cold chain coverage. Meanwhile, those figures in US are only 4.51 and 5.25 million ton CO_2 equivalent (CO_2 e). These enormous gaps between the two countries indicate the urgency for China to expand the refrigeration installation coverage especially in meat and aquatic products supply chains. While for the milk category, potentials of GHG emission reductions are relatively small, that 0.39 and 3.64 million ton CO_2 equivalent, respectively for China and US.

The percentages are much noteworthy. In meat category, 51.9% and 29.3% of current GHG emissions from China and US can be avoided, respectively. And in aquatic products category, these figures are 84.2% and 79.8%. Compared with the huge potentials in meat and aquatic products, milk displays relatively smaller percentage of GHG emission reduction that 3.16% and 14.0% of current GHG emissions from China and US can be avoided. Besides the overall changes in GHG emission reduction, it is also necessary to examine the tradeoffs between the emissions associated with the reduced food loss and those associated with the cold chain.



(a) Meat (b) Milk

(c) Aquatic products

Figure 4 Structural changes of GHG emission reduction in CN and US

Fig. 4 illustrates the structural changes within the total GHG emission changes. The orange part indicates the GHG emissions associated with food loss, and the green part indicates the GHG emissions associated with the use of refrigeration. With no doubt, the expansion of cold chain contributes to the increase of energy consumption, but decreases the food loss. However, in all food categories from both countries, the GHG emission reduced due to the increased avoided food loss exceeds those related to the expansion of cold chain, which contributes the total reduction of carbon emissions in both countries and all food categories. As marked with the absolute changes in food loss decrease and energy consumption increase, the benefits of cold chain expansion brought in reduce carbon emissions are obvious.

However, two facts must be noticed in these comparisons:

(1) The efficiencies of cold chain between different food categories are different;

This is certain. The category is different, thus the physical and chemical characteristics are different. However, this indicates that potentials for expansion of cold chain will vary depends on the product type. For instance, potentials for milk are relatively small compared with those of meat or aquatic products in this analysis, despite the demand differences.

(2) The penetration effects of energy against food between China and US are different;

This is much noteworthy, because it has been assumed that the refrigeration efficiency between China and US are the same. Thus, there should be factors other than refrigeration facilities that affecting the penetration between energy consumption and food loss.

For the first fact, the efficiencies indicate the penetration of energy consumption increased against the food loss avoided due to the expansion of cold chain. Fig. 5 illustrates the efficiencies of different food categories between China and US, in which the slope represents the amount of food loss avoided for per unit of energy consumption by cold chain.

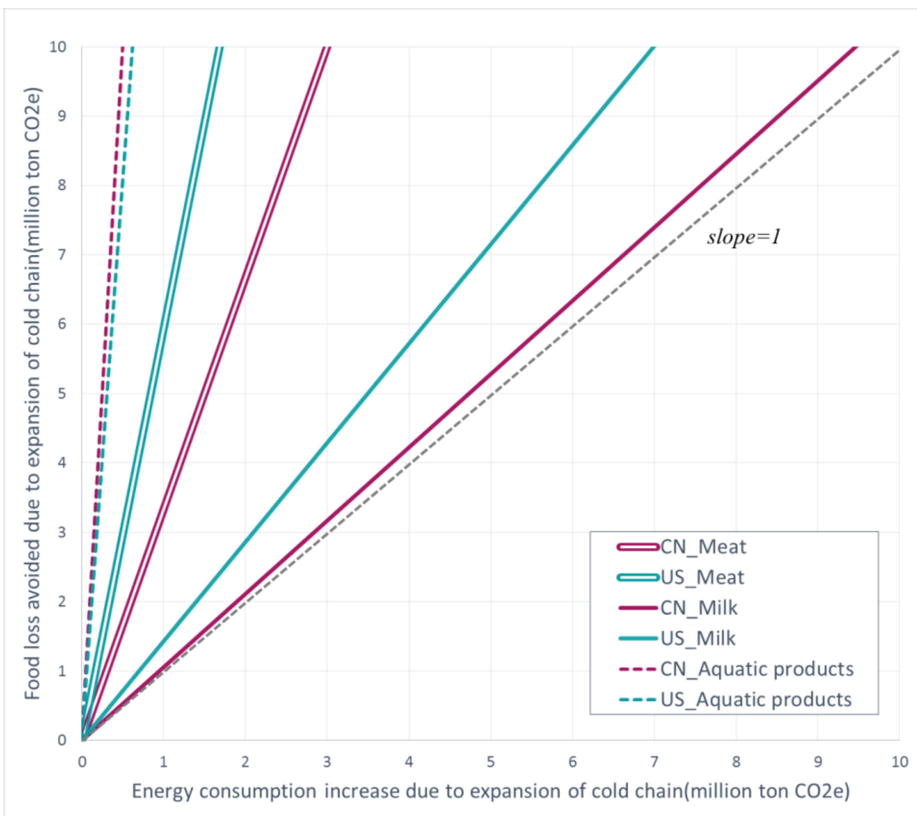


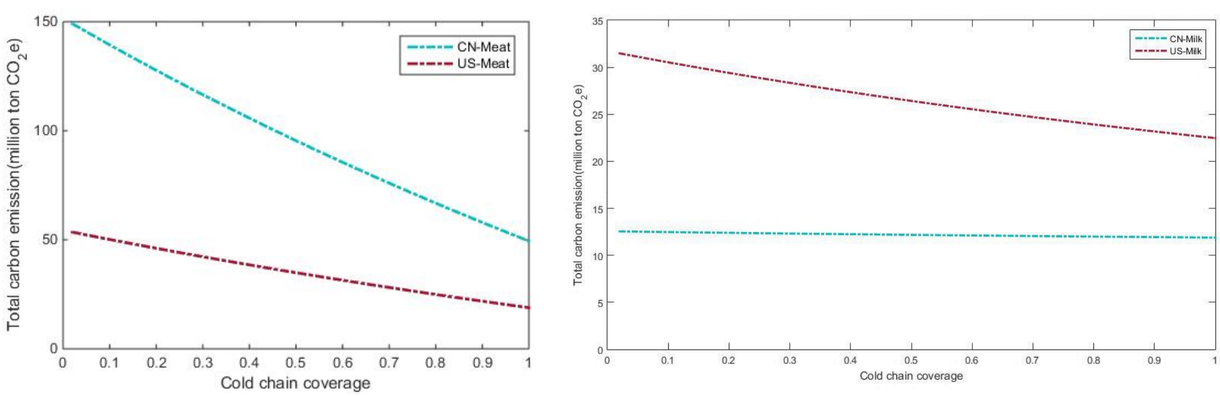
Figure 5 Penetration between energy consumption and food loss

In Fig. 5, the x-axis indicates the "increased" energy consumption (in carbon emission) due to the expansion of cold chain, while y-axis indicates the "avoided" food loss (in carbon emission) as a result of the expansion of cold chain. The lines represent the penetrations between the avoided food loss and the increased energy consumptions in different food categories and in China and US.

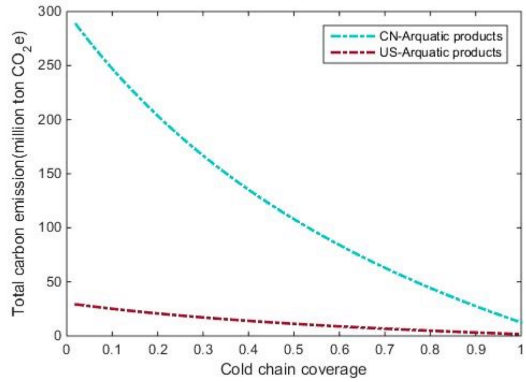
A grey dash line is added in Fig. 6 to represent as a standard line, of which the slope is 1. This indicates the "efficient" baseline that if the slope of a line is above this grey one, it is efficient in GHG emission reduction for cold chain, and vice versus. For milk, both China and US are close to the grey line (CN=1.06, US=1.43), while those of meat and aquatic products are averagely over 3 and nearly 6, respectively. This explains why the expansion of cold chain in milk is not that "effective" compared with those in meat and aquatic products. Of course, this is based only on the perspective of GHG emission reduction efficiency. Considering the low total GHG emission level, nutrition benefits and economic values of milk products, the expansion of cold chain for milk is still positive.

The lines can be divided into three groups, that aquatic products in China and US take the upper positions with the steepest slopes (averagely 19.85 for CN, 16.14 for US), meat take the middle positions with moderate slopes (averagely 3.34 for CN, 5.94 for US), and milk take the bottom positions with relatively flat slopes (averagely 1.06 for CN, 1.43 for US). It is obvious that the differences between food categories (averagely 4.64 for meat, 1.24 for milk, 17.99 for aquatic products) are more obvious than those between countries (averagely 8.08 for CN, 7.83 for US). This reveals that, food's own characteristics are casting much stronger impacts on cold chain's potentials in GHG emission reduction both in China and US, which is consistent with fact (1) that penetrations between food loss and energy consumption vary depends on food products, resulting the differences in potentials of GHG emission reduction.

For the second fact, the differences between countries are more noteworthy. Fig. 6 displays the trend of GHG emission with the expansion of cold chain coverage, that the slopes of the curves between China and US in the same food category and with the same cold chain coverage are different.



(a) meat (b) milk



(c) aquatic products

Figure 6 Total GHG emission trends with cold chain coverage

It should be noticed that the two lines are displaying obviously different trends. As the refrigeration efficiency has been assumed similar, what result these total GHG emission gaps are population and the carbon footprints of food and energy.

Fig. 7 suggests the carbon footprints of the investigated food products and electricity generation between China and the US. Differences are obvious that China has an averagely higher carbon emission level in all food products and electricity. This is believed associated with the regional differences and local conditions. For instance, the carbon footprint differences in specific meat products, including beef, pork, poultry and lamb, are contributing a total of 1.75kg CO2e/Kg higher in China than the US. So is the case in other food category and electricity generation.

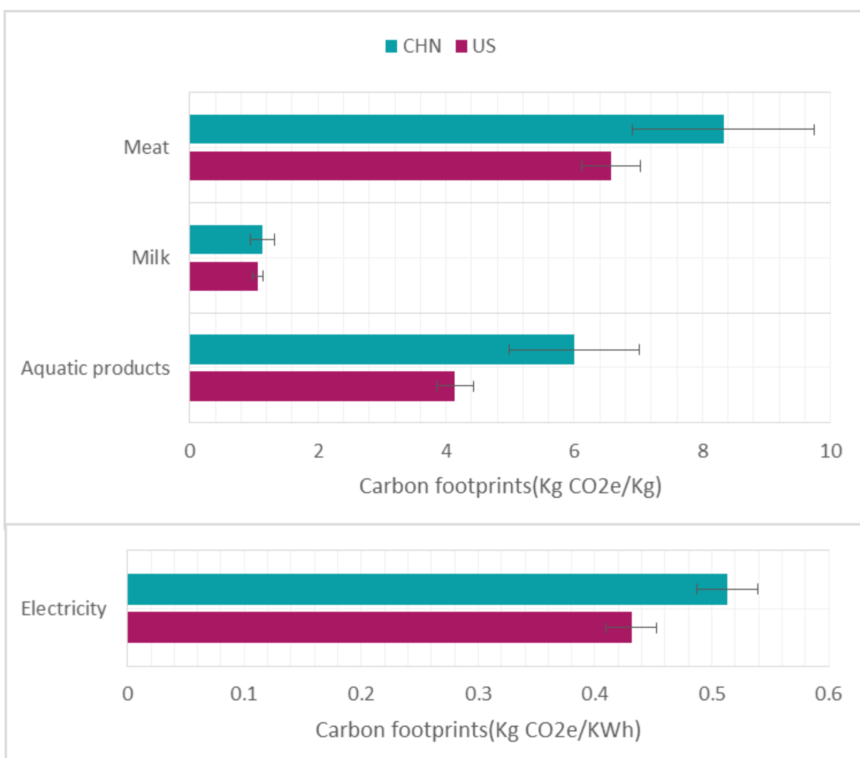


Figure 7 Carbon footprints of food and electricity between China and the US

Besides, structural differences are also contributing. Fig. 8 demonstrates the meat and electricity structures in China and US, which show that China possesses a pork-dominated meat structure and coal-dominated electricity structure, while US has a high portion of poultry and beef in meat, and natural gas, coal and nuclear in electricity structure, which as a consequence are reflected in the differences of carbon footprints between the two countries. According the IEA and EIA, 58% of China's electricity is powered by coal, compared with 53.5% in US is natural gas and nuclear, resulting an averagely 0.08 kg CO2e/KWh higher from electricity in China.

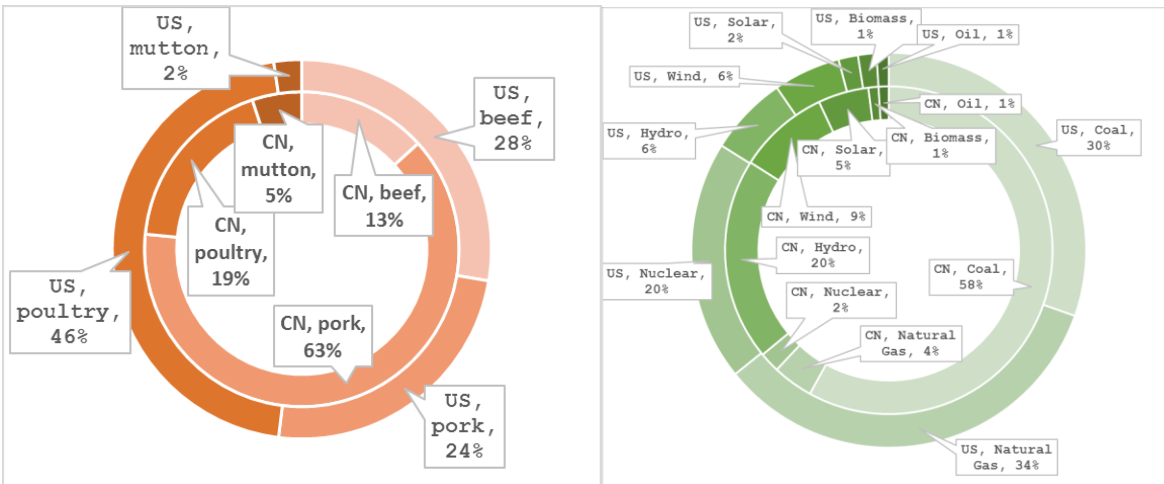
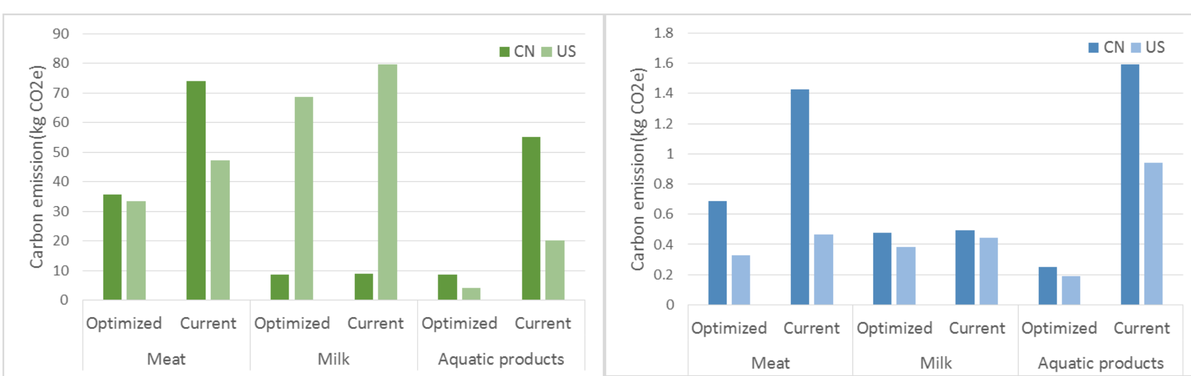


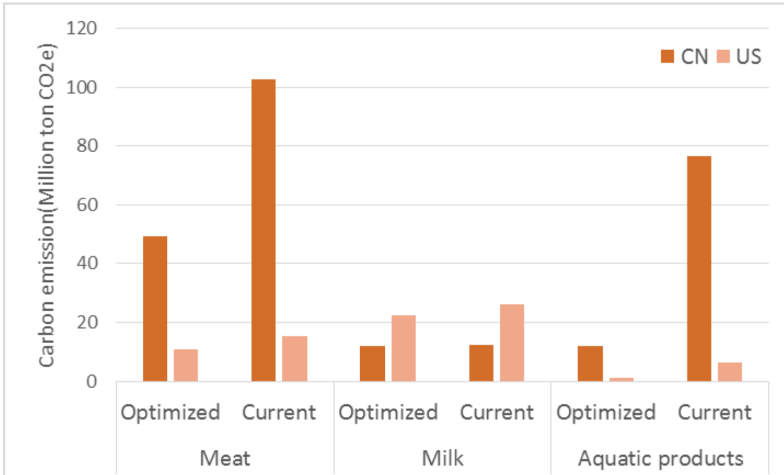
Figure 8 Meat and Electricity structure in CN and US

As the consequences of carbon footprint differences in specific food products and electricity, the cold chains' penetration efficiency in China and US are obviously affected. As displayed in Fig. 9a's optimized groups, differences in GHG emissions from per unit of food output are still obvious (US are 51.79%, 20.51% and 24.52% less than China in meat, milk and aquatic products) even both at fully covered cold chain conditions. However, when comes to the personal level, these figures go totally different (US are only 6.27% less than China in meat, but are 703.82% higher in milk and 53.17% in aquatic products) due to the differences in personal food consumption (Fig. 9b's optimized group). Finally, these micro-scope differences are further amplified by the giant differences of population between the two countries (Fig. 9c).



(a) Carbon emissions per unit of food output
(b) Carbon emissions per capita

(food loss+ energy) (food loss + energy)



(c) Total carbon emissions (food loss + energy)

Figure 9 Comparisons of GHG emission changes between CN and US

4. Discussion

In this paper, it is highlighted that the expansion of cold chain can result an overall decrease on carbon emissions in food systems, however the effects vary from food categories to countries. Based on the calculations, in both countries and in all food categories, the GHG emissions from the reduced food loss exceed those from the increased energy consumptions at the current level of final food demands during the expansion of cold chain. Thus, this paper highlights that, either in China or the US, regardless of the current status of cold chain, the increased installation of refrigerated food supply chain will reduce the total GHG emission of the food system, which could further be used to support and stress cold chain's benefits not only to public health, but also to climate change

In addition, results also reveal that the potentials of GHG emission reduction from cold chain vary from food type to country, due to the differences in characteristics between food categories, and carbon footprints of food and electricity between China and US. Differences between food categories show much stronger impacts than those between countries. Penetrations between food loss and energy consumption by cold chain in aquatic products and meat display averagely 1447% and 373%, respectively, against those in milk. On the other hand, differences in diet structure, electricity structure and carbon footprints of both food and energy products also contribute to the gaps in cold chains' GHG emission reductions between China and US.

These findings are relevant to a number of stakeholders. Policy makers can use this paper to help designing different GHG emission schedules based on the domestic food consuming pattern and carbon footprints of domestic products. Manufacturers of refrigeration equipment and providers of refrigerated logistics services can improve the equipment efficiency and design professional equipment, and delivery network for specific food products so as to mitigate the carbon emissions. Scholars can propose related development plans for community nutrition improvement and GHG emission reduction based on local circumstances.

The results in this paper are based on the assumption that the installed refrigeration devices and settings are the similar between developing and developed countries during the expansion of the cold chain. However, considering the current gaps between developing and developed countries in technology (Ashok, A., et al., 2017) and management efficiency (Ndraha, N., et al., 2019) in food supply chain, this indicates that besides increasing the installation of cold chain infrastructure, closing the gap by applying more advanced equipment and more strict regulations on temperature control (Ndraha, N., et al., 2018) and food processing (Wang, K.Y. and Yip, T.L., 2018) is also necessary.

As described in the former part, cold chain can be regarded as a carbon-efficient technology that transfer the carbon investment from food production to refrigeration, which is consistent with the descriptions in Fig. 6. When cold chain coverage is low, initial food inputs have to be increased so that the final demands could be meet, at which circumstance the differences in food carbon footprints between China and US are emphasized; on the other hand, when cold chain coverage is high, initial food inputs are at the lowest level and the energy consumption of cold chain is at the highest level, making the differences in electricity carbon footprints more emphasized. Thus the penetration efficiency associated with the energy consumption and food loss is also important (Badia-Melis, R., et al., 2018;).

Results show that besides cold chain infrastructures, other factors along the supply chain are also casting influences on the penetration, including the carbon footprint in the production of food, diet structure and electricity structure. These factors and related results, which are barely mentioned in existing papers, can be reflected in the priority of installation of cold chain in certain food category, the optimization of energy structure, or the related regulations design (Porter, S., et al., 2016). For instance, results suggest that specific food products have a much higher penetration efficiency between food loss and energy consumption that aquatic foods are 1447% over milk, and meat is 372% over milk. In combination with the huge consumption, diet structure and current installation level of cold chain in China, these findings may probably support the decision making for the priority of cold chain expansion in China. On the other hand, as noted by Heard (2019), the introduction of cold chain may cause the diet shift in the final food demands, resulting the food consuming patterns in developing countries more “similar” to those in developed countries, and so will the energy consuming and the GHG emission patterns. However, this is premised on the “similarity” also happens in other related factors, including supply structure of power generation, and carbon footprints of food products and energy across different countries in different development process. According to this paper’s results, the carbon footprint gaps between China and US in food and electricity production will be amplified even at the same cold chain installation level, because of the huge consumption and structural differences in diet and energy system. This indicates that the coverage rate of refrigerated food supply chain is not the only factor that will affect cold chain’s potentials in GHG emission reduction. In extreme conditions in our simulations of China’s milk cases, results suggest the optimum may happen at a zero refrigeration-installed supply chain where only coal and natural gas powered electricity are considered. This is meaningful in Central and Northern China, where China’s main milk producing ranches locate and coal dominates the local electricity generation structure. As the Chinese diet structure shifts, the milk consumption is expected to grow continuously, this is worth paying attention to.

In addition, the transport & storage time is also an important factor. In this paper, the results are based on an average food transport & storage time from GFCCC (Global Food Cold Chain Council). However, when considering the uncertain transport distances and the versatile cooking ways especially of the aquatic and meat products in both countries, the results might change accordingly. For instance, the results might be smaller if more products are supplied locally and faster. However, accurate results are not provided in this paper, due to the lack of precise data. Considering the rapid development and huge market potentials of cold chain in emerging food systems, the construction and application of high volume database and intelligent system for precise cold chain management and GHG emission reduction are also essential in the future.

This paper intends to investigate the trade-offs between energy consumption and food loss during the expansion of cold chain from the perspective of GHG emission reduction. Results highlight cold chains' positive contribution on mitigating climate change, but are not providing precise figures due to the lack of detailed and accurate data. Meanwhile, calculations in this paper are based on assumptions mentioned in 2.3, which means China's potentials of GHG emission reduction are probably underestimated because the currently relatively low refrigeration efficiency compared with the US. Furthermore, the improvement of technology during the expansion of cold chain is also not included here. This improvement not only refers to the development of refrigeration, but also the advancement of food production and energy generation, which could be further investigated in the future works.

5. Conclusion

This paper investigates the trade-offs between food loss and energy consumption during the expansion of cold chain, diagnoses the differences in GHG emission reduction potentials by determining the optimal scale of cold chain system in specific food categories, and examines the penetrations efficiency of the trade-offs between developing and developed countries. China and US are selected and compared as case studies. Results highlight the expansion of cold chain and suggest that cold chains' potentials in GHG emission reduction vary from food categories to countries. In addition, diet structure, energy structure and carbon footprints of food and electricity are also affecting the potentials of GHG emission reduction of cold chain.

The conclusions in the paper are listed as follows:

(1) The GHG emissions from the reduced food loss exceeds those from the increased energy consumption during the expansion of the cold chain. Results from China and US in meat, milk and aquatic products all suggest that optimums will occur at the fully covered refrigerated food supply chain and can result approximately 51.93% and 29.34% reduction of current level of GHG emission in China and US respectively in meat, 3.16% and 14.01% in milk, and 84.17% and 79.75% in aquatic products.

(2) The penetrations between food loss and energy consumption of cold chain vary on specific food and between countries. Aquatic products have an averagely 1447% penetration rate over milk, and meat 372% over milk, indicating a higher priority of installation of cold chain infrastructure in aquatic products and meat. However, this should be considered in combination with total consumption of the food.

(3) The carbon footprints of food and electricity affect the GHG emission reductions potentials of cold chain. Even assumed with similar equipment efficiency, China still has a lower penetration efficiency compare with US, due to the higher carbon foot prints in food and electricity. Moreover, this gap will be amplified by the diet structure, energy structure and huge consumption in China.

The introduction of cold chain in developing countries has a comprehensive benefits, including the public health improvements and GHG emission reduction. While incorporating the cold chain itself, this analysis intends to provide a comprehensive view on the environmental impacts of cold chain to better support the sustainable development of food system worldwide.

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