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A SYSTEMS APPROACH TO CARBON POLICY FOR FRUIT SUPPLY CHAINS: CARBON-TAX, INNOVATION IN STORAGE TECHNOLGIES OR LAND-SPARING?

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Abstract

Reducing CO2 emissions of food supply chains has increasingly received attention from businesses and policymakers. Various options have been identified, including improving production efficiency[25, 26, 27, 29]; implementing land sparing strategies[30, 35]; proposing policies that influence businesses' decisions[5]; or developing innovative technologies aiming at lowering GHG emissions. When proposing new policies to reduce CO2 emissions, policy makers favor tools that are informative in the economic and environmental dimensions simultaneously. Hence, we offer a systems' based approach to simultaneously assess the environmental and economic impact of alternative strategies to reduce CO2 emissions in food supply chains. To this end, we develop a detailed spatially- and temporally-disaggregated price equilibrium mathematical model for a food production and distribution system with an application to the U.S. apple supply chain. We considered three alternative emission reduction interventions: a carbon-tax, a land sparing incentive, and an emission-reduction new technology. Our findings suggest that carbon-tax has the potential to reduce CO2 emissions; however, at the cost of increasing consumer price and reducing apple production quantities (due to the increase in production cost) and thus compromising food security on the long run. On the other hand, we demonstrate that the potential of land sparing strategy to offset CO2 emissions depends heavily on spatial characteristics of the spared land. The success of land sparing strategy is driven mainly by the high carbon sequestration rates of spared land, a privilege that not all areas enjoy at the same level when implementing in a global scale. Nevertheless, we find that an R&D strategy yielding improved storage technologies with lower CO2 emission rates has the greatest potential to reduce CO2 emissions in the apple supply chain in the U.S.

The global food system, from fertilizer manufacture to food storage and packaging to retailing, is responsible for up to one third of all human-caused greenhouse-gas (GHG) emissions[36]. A considerable amount of the total food intake by mass (30%) is represented by fruits and vegetables, which constitute the largest food group consumed worldwide[43]. Fruit Supply Chains (FSC) are an important component of this system, and they play an important role in todays' economy, as consumer demand for healthier diets and fresh products is increasing. The shift toward increased demand for fresh fruits and vegetables is happening in the context of increased concern over global climate change and the resulting challenges for the food system. The recent debate at the Convention of the Parties of the United Nations Framework on Climate Change (COP21) attests to this concern and to the range of viewpoints on how to reduce CO2 emissions. In the context of food systems in particular, the COP21 calls for strategies that include agricultural intensification (i.e. land sparing from production agriculture), food waste reduction in production and distribution, development of CO2-efficient postharvest technologies, and policies to influence behavior of private decision makers (e.g. consumers, businesses), among others[1, 2]. Reducing CO2 emissions originating in agriculture/food supply chains is challenging because the reductions achievable by changing farming practices are limited[2, 3] and are hampered by rapidly rising food demand[4, 5]. Hence, interventions to reduce CO2 emissions from agriculture/food supply chain human activities require rigorous approaches that take into account environmental and economic impacts simultaneously.

FSCs possess a set of unique features that require substantial amounts of energy and thus contribute substantially to CO2 emissions. Storage is required to keep fruits fresh, healthy, and consumable during non-harvest seasons, however fruit storage is strongly connected to the energy sector, which is the largest contributor to CO2 emissions globally[39-41]. About 15% of the electricity consumed worldwide is used for refrigeration alone[44]. The production of field grown fruit involves the consumption of energy in farm machinery as well as in the manufacture of the various agricultural inputs such as fertilizers and pesticides entailing an additional use of energy[47]. Cooling during transportation and the emissions associated with transportation trucks constitutes additional CO2 sources from FSCs. Moreover, a study by[43] presented the life cycle assessment of 34 fruit and vegetable products sold by a large Swiss retailer, showing that shipping fruits and vegetables is the dominating factor for carbon footprint when compared against seedling production, farm machinery use, fuels for the heating of greenhouses, irrigation, fertilizers and pesticides. Hence, reducing CO2 emissions due to different activities of fruit supply chains systems globally can play a significant role in stabilizing GHGs.

This study offers a systems approach to evaluate alternative CO2 reduction emission strategies in FSCs taking into consideration economic and environmental dimensions simultaneously. Our methodology is based on solving a spatially- and temporally-disaggregated price equilibrium mathematical model following the work of[19] to estimate optimal product flows from supply regions to consumption locations. The model is spatial and considers unique characteristics of different production or consumption locations (e.g. supply functions, carbon sequestration in forest and consumer preferences). Furthermore, the temporal dimension is critical because fruit production is mostly seasonal. In our model, the decision variables are production, consumption, export and import quantities; producer prices for each supply region; retail prices for each consumption location; inter-regional commodity flows; and producers' and consumers' economic surplus (see Supplemental Material section for a detailed description of the mathematical model). The methodology employed here is robust enough to be applied to any FSC in any country worldwide.

We apply our model to the case of the U.S apple supply chain. The U.S. is the second largest apple producer worldwide after China and apples rank second after bananas in terms of fruit consumed in the country. Furthermore, the apple supply chain is an excellent case due to its seasonal production and storage requirements which is common in most fruits. We consider apple production in California, Pennsylvania, Virginia, New York, Michigan and Washington and forty-nine consumption locations, each corresponding to the country's continental states. We take into account five fresh apple varieties (Red Delicious, Golden Delicious, Granny Smith, Gala and All others) to accommodate regional specialization on specific varieties (e.g. Granny Smith in Washington) and regional differences in consumer preferences. Apples are produced only in the harvest season (typically, September through November in the northern hemisphere. After harvest, they are either shipped directly to consumers, put into short-term storage; or put into long-term storage for shipment during the non-harvest season. The model is inter-temporal and, considers two time periods: (1) the harvest season (September to December), during which apples are primarily put into short-term storage prior to distribution; and (2) the non-harvest season (January to August), when apples are put into long-term Controlled Atmosphere (CA) storage. Our model takes into account exports and imports of fresh apples. The primary transportation method employed in our model is heavy-duty diesel trucks which account for approximately 95 percent of total apple transportation[42]. Apple production from the six states included in the analysis constitutes more than 90% of apple production in the U.S. (see Supplement Material for a detailed description of the model specification).

To parametrize the model, we first identify all activities responsible for emitting CO2 gases including production, storage and packing, and transportation activities. Subsequently, we calculate the corresponding CO2 emissions from each activity. Then, we calculate production yields for each region as well as sequestration rates from apple orchards. Next, we estimate demand and supply functions based on price elasticities estimations for each production region and each demand location (see Supplement Material). As of cost and profit components, the model considers production cost of each apple variety in each state, electricity price for storage, and shipping cost (see Supplement Materials for more details).

We formulate three strategies to mitigate CO2 emissions: 1) a carbon-tax to penalize emissions; 2) a land-sparing mechanism in which apple production yields increase, allowing some orchards lands to be converted to forests that sequester CO2; and 3) R&D investments in storage technology resulting in new storage technologies that emit less CO2 rates. In order to illustrate the impact of different scenarios under each strategy we follow a simulation based approach to generate the scenarios. To this end, we define a simulation parameter (k) to generate several scenarios using different values of k where $k \in [0,1]$. For the carbon-tax strategy, we assume that taxes are in the range of \$50-500 per CO2 metric ton, following the recommendation found in[20]. The tax rates per CO2 metric ton is $50 + k * (500 - 50)$where k is the simulation parameter varying from 0 to 1. As for the second strategy, we need to specify an improvement in production yields to allow certain area of land to be spared in order to maintain the same level of production. In the second strategy, we assumed an increase in production yield in a linear fashion, assuming that current level of production yield provides a Lower Bound (LB) of yield in the future, we assume an Upper Bound (UB) of 100% increase in production yield. Hence, the output can be expressed as $Production\ level = LB + k * (UB - LB)$. As production yields increase, the area of orchards required to achieve the same level of production quantity declines allowing land to be spared; thus $Area\ of\ spared\ land = k * Orchard\ Area$. Spared land is then used to restore natural habitats on the land spared, in our case we assumed forest restoration on spared lands, which have higher sequestration rates than the apple orchards. Sequestration rates are spatial, depending on soil, climate conditions and other factors. Carbon sequestration rates are available in the Supplement Material. In the third strategy, we assume that R&D investments on storage technologies manufacturing, resulting in new innovative technologies that emit less CO2 gases[46]. We assume a linear change in CO2 emission rates due to improvement in storage technologies, with an upper bound of CO2 emissions equal the current levels and a lower bound equals 50% of the upper bound, the CO2 emission rates due to storage activities are calculated as $LB + (1 - k) * (UB - LB)$.

The third step is assessing the economic and environmental impacts of each strategy. We employ CO2 emission quantities as a measure of environmental impact; apple production quantities, total surplus (producer and consumer) and producer and retailer prices in each region as a measure of economic impact.

Figure 1 presents percent CO2 emission reductions as a function of the simulation parameter (k) for several intervention strategies compared against current levels of CO2 emissions. Figure 1 indicates that an intervention strategy leading to new technologies in the storage sector due to investments in the R&D sector offers the greatest potential to mitigate CO2 emissions .

It is difficult at this point to come up with an exact number for the cost of new storage technologies or new production systems, however, we can evaluate the impact of variable storage or production cost on the performance of the U.S. apple supply chain considered in this study. If we assume that producers acquire new storage or production technologies and project this asset fixed cost as part of the storage or production variable cost resulting in higher rates in their variable cost, then our model can easily accommodate for this change by simply change the current storage or production cost per pound, see Supplement Material for more details about the spatially- and temporally-disaggregated price equilibrium mathematical model. To this end, we run several simulation experiments to investigate the impact of such increase in storage or production cost on the performance of the apple supply chain. We found that if the new storage cost is doubled, consumer price will go up by less than %1. Likewise, increase in production cost due to new production technologies by two folds will increase consumer price by less than %1. The main intuition behind this slight increase in consumer price is that storage or production costs represent a small portion of apple total production cost given that labor and ownership costs remain unaffected by the introduction of this new technologies, see Supplement Material for more details about cost structure of apple production in the U.S.

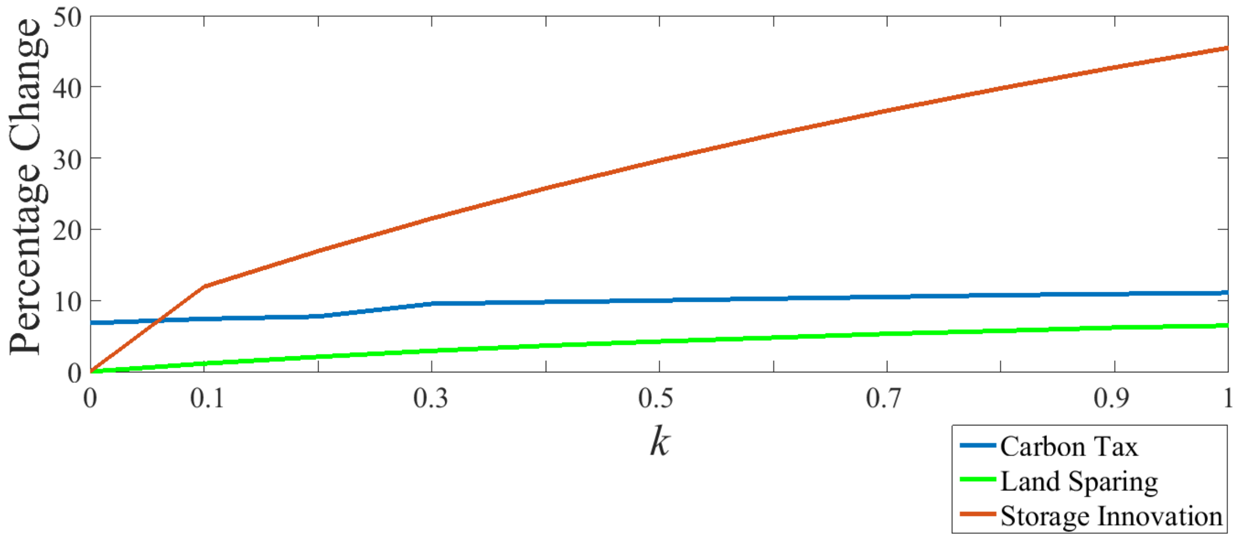


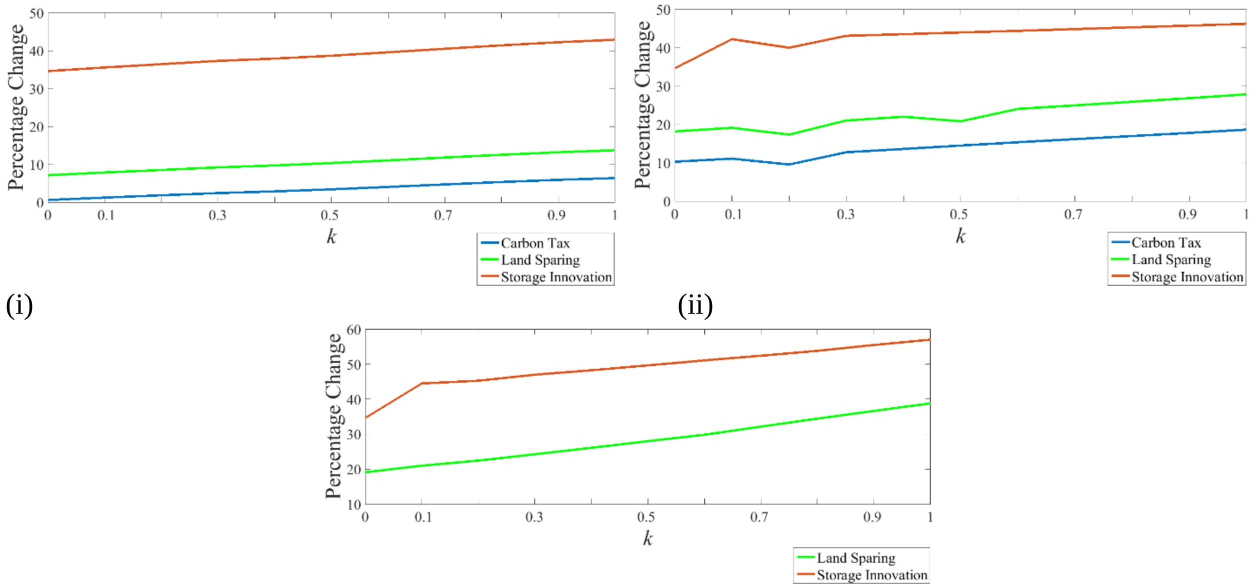
Figure 1: Percent decrease in CO2 emissions due to each strategy compared to the current level of CO2 emissions.

As shown in Figure 1, innovation in storage technologies has the potential to reduce CO2 emissions to a greater extent than land sparing (e.g., 45.5% versus 6.45% for $k = 1$). Indeed, the success of land sparing depends on many factors including carbon sequestration rates. Lamb et al.[30] focused on the case of UK's agriculture system to show that land sparing has the potential of mitigating CO2 emissions by 80%. However, carbon sequestration rates in the U.S. eco-systems are different from those in the UK. While carbon sequestration rates depend on several factors such as forest management[48, 49], we investigate the potential of increasing carbon sequestration rates in selected regions at different increased rates. Our results suggest that if the carbon sequestration rates are four times the current sequestration rates in each production region, land sparing can offer the same level of CO2 mitigation as improvement in storage technologies. While land sparing provides the potential to reduce CO2 emissions, this strategy depends heavily on spatial characteristics affecting sequestration rates. On the other hand, the degree to which new storage technologies can reduce CO2 emissions depend on local climate conditions and products under considerations. That is, for regions experiencing higher temperatures the need for storage becomes more important. Given the current trend in global warming, the need for new innovative storage technologies becomes even more important[45]. Furthermore, different perishable, fruit or food products require different storage temperature; hence for products that requires continuous refrigeration, storage technologies emitting less CO2 rates have greater potential to reduce CO2 emissions by larger quantities.

To further explore interventions to reduce CO2 emissions in FSCs, we identify additional strategies which modify or combine the three strategies discussed above. Specifically, we simulate three variations of a carbon-tax strategy: 1) a carbon-tax imposed on production activities emitting CO2 gases; 2) a carbon-tax imposed on CO2 emissions from storage activities; and 3) a carbon-tax imposed on all activities emitting CO2, see Table 1 strategies 1-3. In addition, we consider land sparing approaches in combination with carbon tax on all activities, on production activities only, and on storage activities only (strategies 4-6, Table 1). Similarly, we examine innovation in storage technology in combination with the same carbon tax strategies (strategies 7-9, Table 1). Interventions considering a combination of land sparing and innovation in storage technologies with carbon tax on transportation activities are excluded since the share of CO2 emissions from transportation is small (9% in our case study). In the subsequent discussion we assume that the value of the simulation parameter $k=1$ for land sparing and improvement in storage technology (i.e., 100% improvement in production yield allowing 50% of land to be spared and storage technologies that emit 50% CO2 rates compared to current levels), while we change the value of the simulation parameter k for carbon tax levels to analyze how different values of carbon tax interact with land sparing and improvement of storage technologies if fully realized (i.e. $k=1$). Furthermore, we change the lower and upper bounds of carbon taxes, the new lower bound is $500 for each ton of CO2 emissions while the upper bound is $5000. We opt to change the bounds of carbon tax to magnify the impact of taxes on the land sparing and innovation in storage technologies interventions.

Table 1: Additional Interventions to reduce CO2 emissions

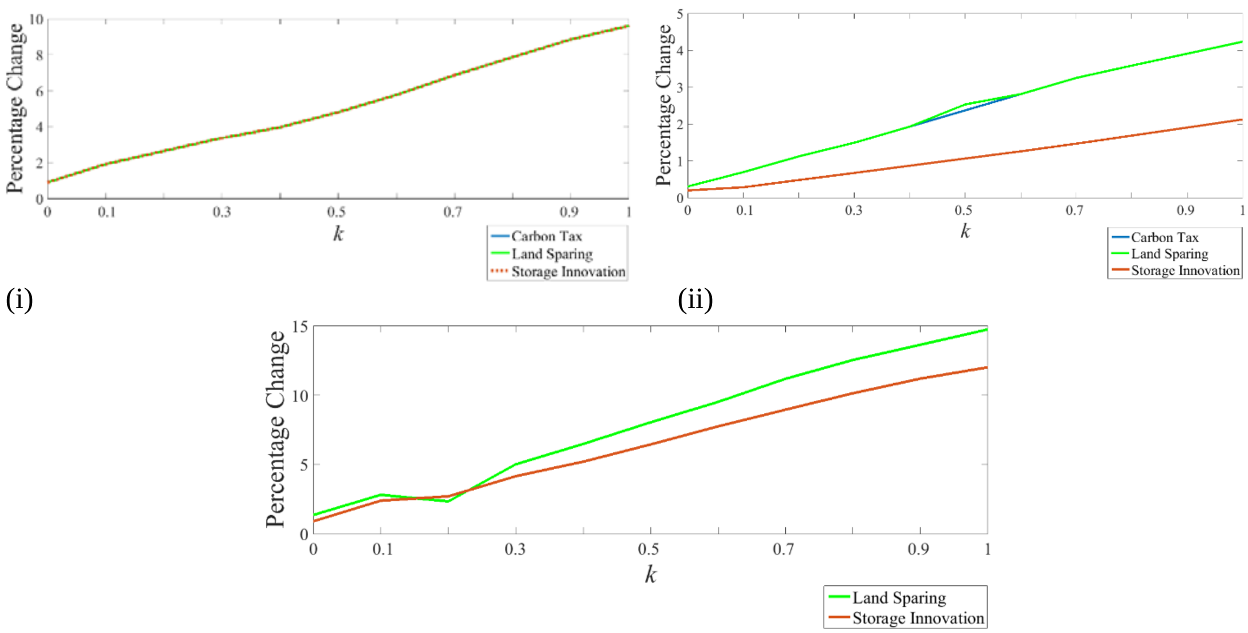
Main Strategy	**Variation**
Carbon Tax	1. Carbon tax on production activities.
	2. Carbon tax on storage activities.
	3. Carbon tax on transportation activities.
Land Sparing	4. Land Sparing with carbon tax on production, storage and transportation activities.
	5. Land Sparing with carbon tax on production activities.
	6. Land Sparing with carbon tax on storage activities.
Innovation in Storage technologies	7. Innovation in Storage technologies with tax on production, storage and transportation activities
	8. Innovation in Storage technologies with tax on production activities
	9. Innovation in Storage technologies with tax on storage activities



(i) (ii)

(iii)

Figure 2a, taxes are imposed on activities emitting CO2 due to (i) production only, (iii) storage only, and all activities in the FSC.



(i) (ii)

(iii)

Figure 2b, taxes are imposed on activities emitting CO2 due to (i) production only, (iii) storage only, and all activities in the FSC.

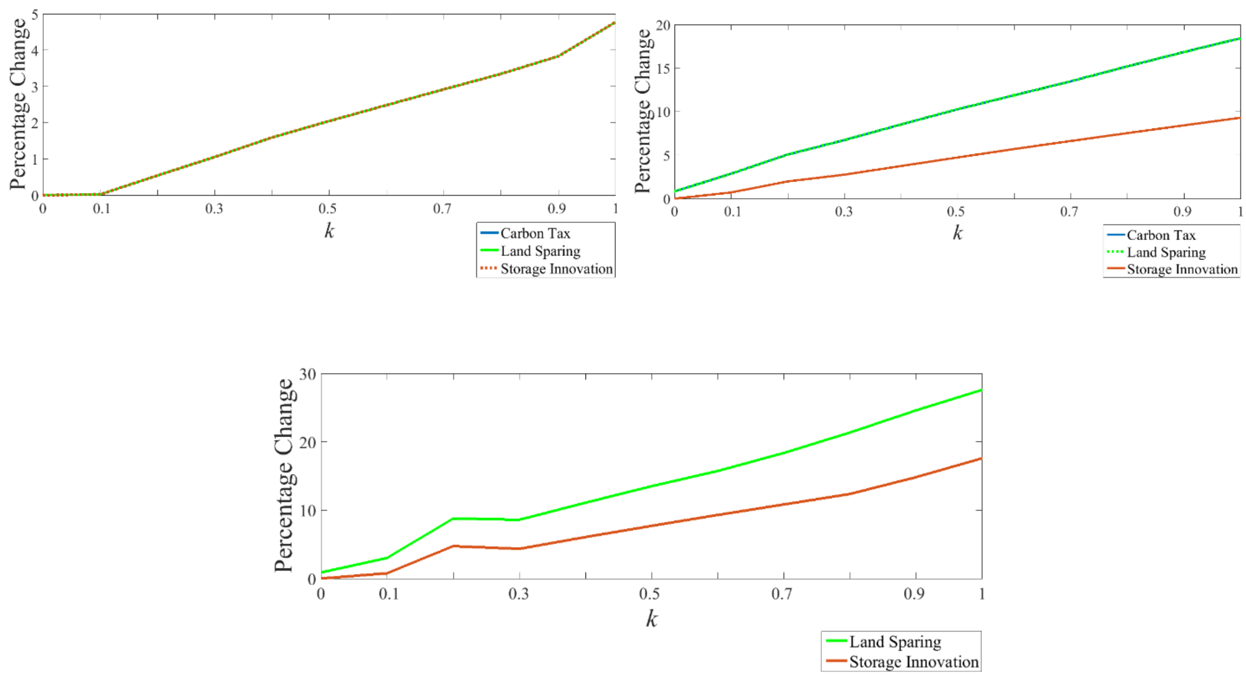


Figure 2c, taxes are imposed on production activities only part (i), storage activities only part (ii), and all activities emitting CO2 part (iii)

Figure 2: (a): Percent decrease in CO2 emissions under each strategy compared to the current level of CO2 emissions. (b) Percent decrease in apple production quantities under each strategy compared to the current level of CO2 emissions. (c): Percent increase in consumer price calculated as an average across all states under each tax strategy compared to the current average consumer price.

Figure 2 suggests that strategies combining a carbon-tax with innovation in storage technologies demonstrate more potential to reduce CO2 emissions in all cases. Furthermore, storage innovation with carbon tax strategies provide superior economic impacts (see Figures 2b and 2c). Figure 2b indicates that the largest reductions in apple production occur through carbon tax strategies or carbon tax and land sparing. In contrast, strategies combining a carbon tax with innovation in storage technologies have smaller impact on apple production. The reason is that CO2 emission reductions from storage surpass the net reduction in CO2 emissions due to land sparing. Therefore, improvements on storage technology reduce the cost component due to CO2 emissions and hence provide wider window of feasible operations to growers and packer-shippers; on the other hand, land sparing and carbon tax strategies make apple production economically infeasible when CO2 emissions cost reaches a certain threshold.

A critical economic aspect of initiatives to reduce emissions is their impact on prices paid by consumers. Figure 2c compares the strategies in terms of their impact on apple retail prices. For the same level of reduction in CO2 emissions, carbon-tax and innovation in storage technologies provide the lowest increase in apple price per lb. (i.e. lower increase in prices) for consumers. Similarly, for a given consumer price, carbon-tax and innovation in storage technologies achieves highest reduction in CO2 emissions.

Our analysis suggests that innovation in storage technologies has a great potential to reduce CO2 emissions in the U.S. apple supply chain. We argue that innovation in storage technologies can contribute to mitigate CO2 emissions globally. Many food supply chains, as well as other perishable products supply chains such as pharmaceutics, are characterized as 'cold chains' where continuous refrigeration is used to extend and ensure the shelf life of fresh and processed foods/products[50]. This, together with the fact that consumer expect to have a wide variety of fresh produce available year round, underscores the critical role that innovation in storage technologies will play in initiatives to reduce CO2 emissions in years to come. Furthermore, James and James[45] point out that use of refrigeration is likely to increase with rises in average ambient temperatures due to global warming, and this will increase associated GHG emissions. Hence, we argue that the realization of CO2 emissions mitigation due to storage activities would have far reaching implications on a global scale. Furthermore, as highlighted in the analysis, the success of land sparing to mitigate CO2 emissions depends highly on carbon sequestration rates, a privilege that may not always lead to same levels of reduction when applied to different regions globally.

We evaluate the impact of carbon tax, land sparing and innovation in storage technologies on the performance of apple FCS in the U.S. The idea of exploring the potential of innovation in storage technologies yielding new technologies that emits less CO2 rates is inspired by a statement by James and James[45]. The authors argue that new/alternative refrigeration systems/cycles such as magnetic refrigeration can have the potential to save energy in the future if applied to food refrigeration; however, none appear to be likely to produce a step change reduction in refrigeration energy consumption within the food industry within the next decade. Nevertheless, formulation and proposal of sound policies to foster investments in the R&D sector of cold storage technologies will make these technologies a reality in relatively short time. Our study then provides a clear evidence that policies targeting investments in R&D sector to yield new technologies in production and storage are essential to reduce CO2 emissions, maintain food security and foster the economy simultaneously. In the U.S. one way to achieve these advancements in through the U.S. Congress, United States Department of Agriculture (USDA) and other legislation bodies to reform the agriculture policies and incentives while in the Europe an obvious mechanism is through some reformation of the EU's Common Agricultural Policy.

As the analysis employs a model with spatial and temporal aspects as well as evaluating the impact of proposed policies on economic environmental dimensions simultaneously, the analysis contributes to the agriculture production systems debate by highlighting the importance of implementing a systems approach to evaluate proposed strategies or policies on economy and environment simultaneously. As we have seen in the previous discussion, measuring one dimension of any strategy may result in misleading recommendation that make some dimensions worse off while optimizing one dimension. Broadly speaking, our model serve as an excellent tool to assist policy makers to carefully examine the impact of policy options to ensure that domestic objectives are maintained as well since the proposed model in our study has spatial and temporal characteristics. Although this study implemented the developed model on the U.S. apple production system, it serves as a model for other agriculture products globally. In our analysis we did not incorporate any technical discussion about how the new storage or production technologies will perform. We assume that the new technologies will be able to improve by two folds. However, enjoying these benefits in practice calls for a new reformation in the agriculture policies by providing incentives to the manufacturers to invest in the R&D sector to yield better storage or production technologies. For instance, the European Common Agriculture Policy (CAP) reformed its policies to dedicate part of its funds to reward farmers implementing land sharing through agri-environmental schemes to balance food production and wildlife preservation [51-53]. Likewise, enjoying the benefits of R&D and land sparing in practice requires re-shaping government subsidy schemes and policies to achieve the desired goals of promoting food production and reduce CO2 emissions. The presentation of potential policy tools and mechanisms to ensure that producers utilize new production or storage technologies is beyond the scope of this article. We leave it to policy makers to design mechanisms ensuring that producers implement new techniques in production or storage technologies; however, implementing market-based measures or subsidy policies reformulation seem to be reasonable options for policy makers.

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