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Abstract title: **Disaster Resilience and Environmentally-Sustainable Food Supply Chains**

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1. Introduction

Natural disasters can have profound negative impacts on food supply chains, and in nations whose economies heavily depend on agriculture, the impact can be devastating. Damage from natural disasters not only affects a food producer's current growing season, but can also cause long-term damage to soils, perennial crops, equipment and infrastructure. Poor nations suffer the most from natural disasters, in part because they often depend on high-risk, low return livelihood systems, such as rainfed agriculture (Sivakumar, 2005a). To make matters worse, the rate of occurrence and the severity of natural disasters have increased significantly in recent years. This paper seeks to determine to what extent established food supply chain disaster mitigation strategies support environmentally sustainable practices.

2. Disasters and Agriculture

The most common types of natural disaster to negatively impact food supply chains are: drought, floods, storms, frost, and high winds (Johnson, 2003). For many regions, these events are commonplace and recurrent features of their climate. For example, some regions have "dry" seasons during which little precipitation is expected. Similarly, floodplain regions experience flood conditions during seasons of heavy rainfall. However, these events can become natural disasters if they are unusually severe or of long duration, if human activity/development has diminished the region's resilience, or if human systems are unprepared or ineffective in managing the negative effects of the event. It should also be noted that one type of disaster can lead to another. For example, a loss of vegetation coverage resulting from drought can lead to future flooding and dust storms.

Droughts

Drought originates from a deficiency of precipitation over an extended period of time, resulting in a water shortage (National Drought Mitigation Center, 2006). However, drought is not a purely physical phenomenon, but also a result of the relationship between natural water availability and human demands for water supply (Sivakumar, 2005a). It can arise even in times of average precipitation as a result of poor soil conditions or agricultural techniques (Motha, 2005). Negative impacts of drought on the food supply chain include poor crop yields or crop failures, soil subsidence, and possible desertification, all of which can devastate a food supply chain. In extreme cases, drought can result in famine, fires and water conflicts.

Floods

Much like drought, destruction caused by floods is a function of climate and soil characteristics. Floods occur primarily when water due to rain or snowmelt accumulates faster than soils can absorb it or rivers can carry it away (Sivakumar, 2005a). Inappropriate human activity/development can also increase the risk of supply chain disruption due to flooding, such as when food is produced in high-risk areas. In some cases this is done intentionally; crops are often grown in floodplains, because the periodic flooding replenishes rich soils and prevents other types of development (King County, 2008). Flooding can also be caused by severe storms, such as hurricanes. In addition to flooding, high winds from severe storms can damage crops and livestock, infrastructure, and food production and storage equipment.

Flooding affects the food supply chain during the growing season and the non-growing season, by causing crop waterlogging, standing crop lodging, soil nutrient loss, loss of pasture use, soil erosion, soil compaction, susceptibility to insects and disease, production disruptions, and permanent damage to perennial crops and farm assets (Sivakumar, 2005a). Flood-saturated soils can lead to poor crop growth (Agriculture and Agri-Foods Canada, 2007). Additionally, flowing floodwater can transport impurities and pollutants, which can contaminate crops and make them unsuitable for human consumption (Gomez, 2005). Flooding caused by tropical storms can also lead to a long-term loss of soil fertility, due to saline deposits over land flooded by seawater.

Frost

"Frost" is a condition in which air temperatures drop below the freezing point of water (Bootsma and Brown, 2009). In the event of frost, crops can be damaged or destroyed (Gomez, 2005). The impact of frost on crop yield and quality depends on the crop variety and its growth stage (Bootsma and Brown, 2009). Damage to crops from frost occurs primarily when air temperatures are colder than expected during a particular part of the growing season.

Wind

High winds can disrupt food supply chains by damaging crops directly, but more often the cause of disaster is severe soil erosion. When soil is dry, uncovered by vegetation, and lacking sufficient organic material, it is at risk for wind erosion. The worst damage occurs when wind follows drought conditions. If wind erosion is allowed to continue over long periods of time, desertification and total loss of soil productivity can occur (Sivakumar, 2005b). One example of an agricultural disaster caused by wind erosion is the "Dust Bowl" that was created in the central plains of the United States in the 1930s.

Synthesis

Table 1 provides a list of recommended disaster mitigation strategies for food supply chains and identifies the types of natural disasters for which these strategies are most appropriate. Most of these practices involve building resiliency into the food production system so that it will be able to withstand disaster conditions. A few strategies, such as use of emergency warning systems and maintenance of seed banks, are more closely related to infrastructure-building for emergency preparedness. In general, however, these strategies involve long-term mitigation; they do not include damage-controlling measures that can only be implemented after a disaster has occurred. While some of the strategies are only applicable to one particular type of disaster, most are common to multiple disaster types. It should be noted that some strategies provide conflicting recommendations; in these cases, the strategy that best meets the needs of a particular food production region should be applied. Each mitigation strategy falls into one of four primary categories: soil, water, plants and animals, or other practices.

3. Environmentally-Sustainable Food Supply Chain Practices

In addition to concerns about resilience in the face of disasters, the importance of environmental sustainability in food supply chains is becoming increasingly recognized. As the world population continues to increase, efforts to produce and distribute large quantities of affordable food rely on methods that are not environmentally-sustainable in the long term. In particular, many food production and distribution practices associated with modern industrial agriculture consume large quantities of fossil fuels, contribute to greenhouse gas production, deplete soil quality, pollute the surrounding ecosystem, and reduce biodiversity. In contrast, an environmentally-sustainable food supply chain is ideally a closed-loop system, reusing many of its outputs as inputs to replenish the system. Table 2 describes environmentally-sustainable characteristics of food supply chains.

Primary Category	Mitigation Strategy	Drought	Flood	Storm	Frost	Wind	Environmentally sustainable?
Soil	Use cover cropping	x	x	x		x	Yes
	Use mulch and leave crop residue in fields	x	x	x		x	Yes
	Fertilize crops to increase their resiliency	x	x				Only if chemical fertilizers are not applied
	Use organic fertilization methods to increase soil organic material levels to better hold soil moistur	x				x	Yes
	Avoid using machinery on saturated soils to minimize compaction		x				Yes
	Test soil for nutrients and apply fertilizer at appropriate times to avoid runoff		x	x			Only if chemical fertilizers are not applied
	Use mechanical tillage to ridge or texture soil, increasing soil particle cohesion					x	No
	Reduce tillage to protect against topsoil erosion		x	x			Yes
Water	Irrigate crops as needed	x					Only if renewable energy is used and water is used sustainably
	Practice water harvesting (rainfall catchment, reservoirs, lakes, ponds)	x	x				Yes
	Only grow crops that can be supported by rainfall	x					Only if biodiversity is maintained
	Use contour bunding to block water runoff in upland crop areas	x	x	x			Neutral
	Monitor soil moisture	x					Yes
	Regulate proper groundwater usage	x					Yes
	Set water entitlements for users	x					Yes
	Divert river water flow to accommodate agricultural areas	x					No
	Replace open-water irrigation channels with enclosed pipelines	x					Yes
	Provide farmers with irrigation scheduling information	x					Yes
	Develop methods to transfer water between neighboring agricultural systems	x					Only if transfer is supported by renewable energy sources
	Encourage installation of water-efficient irrigation technology	x					Yes
Crops & Livestock	Create and maintain a community-based seed bank/nursery	x	x	x			Yes
	Develop crop contingency plans	x					Neutral
	Build emergency sanctuaries for livestock		x	x			Neutral
	Minimize pest damage to crops		x				Only if harmful chemicals are not used
	Use row covers to protect crops				x	x	Neutral
	Use crop rotations	x	x				Yes
	Diversify crop types and planting schedules	x	x	x	x		Yes
	Grow appropriate crop types for region and season	x	x	x	x		Yes
	Practice agroforestry	x	x	x		x	Yes
	Raise livestock as a crop backup	x					Only if livestock are raised using environmentally-sustainable practices
	Maintain pasture land: rotational grazing, replanting	x					Yes
	Develop new drought-resistant crop varieties through breeding and/or genetic modification	x					Long-term effects of GMOs on environment are unknown
	Develop new frost-resistant crop varieties through breeding and/or genetic modification				x		Long-term effects of GMOs on environment are unknown
Other	Develop early warning systems and improved long-range meteorological forecasts	x	x	x	x		Neutral
	Perform risk zone mapping and land use analysis		x	x			Yes
	Build embankments, levees, and adapt river channels for flood diversion		x	x			Only if upstream ecosystem is unharmed
	Build and maintain storm-resistant farm buildings			x			Neutral
	Develop a cropping calendar that includes when to adopt storm measures			x			Neutral
	Construct and maintain emergency food storage facilities	x	x	x			Neutral
	Clear forested areas to reduce the risk of frost in sloping terrain				x		Only if removal is minimal and does not increase erosion risk or reduce biodiversity

Table 1: Recommended mitigation strategies and associated levels of environmental sustainability[1]

1. Sources: Agriculture & Agri-Food Canada (2007), Bootsma & Brown (2009), Das (2005a & b), Dickerson (2004), Doering (1998), Gomez (2005), James, et al. (2009), Pimentel, et. al. (), King County (2008), Pretty (2001), Protz (1999), Sivakumar (2005), Wilhite (2005), Wright (2005)

Food Supply Chain Component	Environmentally-Sustainable System Characteristic
Energy	Independent from nonrenewable inputs
	No net greenhouse gas emissions
Water	Water utilization is balanced with supply
Soil	Effective utilization of soil nutrients
	No nutrient leaching into waterways
	No accumulation of harmful residues in soil
	No net topsoil erosion
Plants & Animals	Biodiversity is maintained
Knowledge & Practices	System makes productive use of the knowledge and skills of farmers

Table 2: Characteristics of environmentally-sustainable food systems (Krejci & Beamon, (2010))

4. Disaster Mitigation and Environmental Sustainability

Resilience to disaster and environmental sustainability are both of great importance to long-term food supply chain sustainability and food security. Therefore, understanding which disaster mitigation strategies are most environmentally-sustainable is critical to designing a robust food supply chain. In Table 1, a description of the environmental sustainability of each of the strategies is provided. Almost all of the strategies are at least somewhat compatible with environmental sustainability, with about half of the strategies (those marked “Yes”) strongly supporting the environment, and about one quarter of the strategies conditionally supporting it. The latter type can either support environmental sustainability or be neutral if the conditions given in Table 1 are met. The strategies that are described as “Neutral” are those that are unlikely to have a direct impact on a food supply chain’s environmental sustainability.

Most of the disaster mitigation strategies that involve soil also support environmental sustainability. These practices all work to maintain or enhance soil structure and fertility, with an aim to preserve its quality in the event of a disaster. However, these same practices also support environmental sustainability as described by the characteristics in Table 2, primarily by avoiding topsoil erosion and making use of naturally-occurring nutrients in the soil. In the long run, these practices can reduce fossil fuel consumption by enhancing soil nutrients without chemical fertilizer, as well as increasing the soil’s capacity to retain moisture, thereby reducing the need for energy required to irrigate. A reduced need to irrigate also conserves water. These practices can also prevent the leaching of nutrients into waterways, an occurrence associated with soil erosion, chemical fertilizers, and over-application of fertilizers. Fortunately, many of these practices are relatively simple and inexpensive to implement. Conservation tilling, mulching, and cover-cropping are all practices that might require training for food producers to implement, but once this knowledge is acquired, the purchase of equipment or chemicals is unnecessary. These practices also have the advantage of protecting the food system against multiple types of disaster.

Mitigation strategies that focus on water usage are primarily focused on resilience of the food supply chain to drought, and the environmental sustainability of these strategies is mixed. Perhaps the most sustainable of these strategies is the practice of water harvesting. This practice takes advantage of a rainy season by storing water while it is plentiful for use when it is not. If the water can be stored in ponds or tanks that are near croplands, the energy required to irrigate will likely be minimal. Additionally, this water catchment strategy will reduce or eliminate the depletion of groundwater sources. Another strategy that has the potential to strongly support environmental sustainability is efficient crop choice. If the crops that are grown during drought seasons or in areas that receive little rainfall are drought-resistant (requiring little water to thrive), then they can be successfully produced with very limited energy and water inputs. The remaining water strategies that support environmental sustainability are those that build efficiencies into irrigation strategies, reducing water wastage and the energy required to irrigate. Of all of these mitigation strategies, water harvesting and drought-resistant crop selection are the most cost-effective and the easiest practices to implement. Both of these practices avoid the need for installing expensive irrigation equipment and heavy reliance on fossil fuels to pump or transport water from distant sources.

Many of the disaster mitigation strategies involving plant crops and livestock also strongly support environmental sustainability. Additionally, many of these sustainable strategies are applicable to multiple different types of disasters. In particular, appropriate crop choices and crop diversity, agroforestry, and maintenance of community seed banks/nurseries are all practices that increase overall food supply chain resilience. By choosing crops that are well-suited to the conditions in which they are grown, farmers can produce food more efficiently, using fewer inputs and yielding greater output. For example, in regions that are prone to flooding, growing rice, which can survive being fully submerged, could be a resilient crop choice. Diversity in crop choices, as well as crop rotations, also mitigate disaster risk; in the event that one type of crop fails from disaster conditions, other crops with greater disaster resilience might survive. This strategy also supports biodiversity, which is a key characteristic of environmental sustainability. Agroforestry is the practice of including trees and other large perennial plants among annual plant crops. This practice is extremely beneficial in mitigating damage from a variety of disaster types. Agroforestry helps to prevent soil erosion by acting as a windbreak during storms. Similarly, it can slow the flow of water to reduce damage to crops in a flood, in addition to absorbing some of the excess water. In terms of environmental sustainability, agroforestry supports biodiversity, adding not only the diverse trees and perennial plants to the landscape, but also providing a habitat for birds and other animals that can act as a non-chemical form of pest reduction. Finally, maintaining a community-based seed bank can help a food-producing community rapidly establish independence from outside food aid after a disaster. Additionally, a well-maintained seed bank can support environmental sustainability through increased biodiversity. Food producers can establish all of these mitigation strategies with planning, training, and coordination.

In general, most of the recommended strategies for disaster mitigation in food supply chains support environmental sustainability to some degree. If implemented, many of these strategies would enhance environmental sustainability. Some of the other strategies can support sustainability, if appropriately implemented, while the remaining strategies generally have minimal impact on the environment. This suggests that in food supply chains, disaster mitigation strategies and environmentally sustainable practices are often mutually supportive. Additionally, the mitigation strategies that best support environmental sustainability are typically simple and relatively inexpensive to implement, making them practical solutions to two major challenges for food supply chains. However, for successful and widespread implementation, educational programs would likely be necessary. Food producers would need to learn the skills required to implement these strategies, as well as understand the potential benefits. Possible support for such training could be provided by government agencies, non-profit organizations, and/or individual communities.

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