Apples, Bananas, and Oranges: Using GIS to Determine Distance Travelled, Energy Use, and Emissions from Imported Fruit

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Abstract

Public interest in food distribution systems as well as an increasing amount of food imports to the United States has resulted in a need for methods of quantifying the transportation of food imports in terms of distance travelled, energy use, and environmental impact. Geographic information systems (GIS) provide a powerful tool to organize and analyze spatial data. This study used a geographic information system to analyze monthly imports of apples, oranges, and bananas in 2008. Shipping routes were mapped, and statistics including average distance travelled, total energy use, and total greenhouse gas emissions were calculated. Bananas were imported in a much larger quantity than apples and bananas, but the average source distance, energy/ton, and emissions/ton measures were lower for bananas than for imported apples and oranges.

Introduction

Producing and distributing food consumes significant amounts of energy. Although food production may consume more energy than food transport, the transportation sector is unique is its dependence on oil (Hendrickson, 1994). Being a fossil fuel, oil is a finite resource, and burning fossil fuel has negative environmental effects (Hendrickson). Growing concern about global warming has resulted in efforts to reduce energy use and greenhouse gas emissions (Meisterling, Samaras, and Schweizer, 2009).

Due to its limited supply, vulnerabilities of oil to changes in supply and demand are also a concern. Rising prices of fuel and food made news across the world in 2008 (Pirog and Rasmussen, 2008). High energy prices were believed to be one of the main contributors to increased food prices (Capehart and Richardson, 2008).

Fuel shortages in the 1970's led to many studies of fuel use in agriculture production and transportation (Hendrickson, 1994). Recently, there has been a renewed interest in local food systems such as farmers markets and community supported agriculture projects (Pirog, Van Pelt, Enshayan, and Cook, 2001).

Pirog and Rasmussen (2008) surveyed 755 customers across the United States in 2008 regarding rising food and fuel prices, environmental issues, and various food systems. Seventy-nine percent responded in agreement that the

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geographic origin of food should be labeled, as long as the product did not cost more (Pirog and Rasmussen). Thirty-eight percent of customers surveyed were willing to pay more for food whose supply chain released 50 percent less greenhouse gases than is normally produced by a conventional supply chain (Pirog and Rasmussen). Consumers and policy makers concerned about energy usage and environmental cost of food transportation need consistent methods for measuring the distance food travels and resulting energy and environmental impact.

Weighted Average Source Distance

A basic measure of food transportation has been referred to as the 'food mile'. Food miles refer to the distance a food product has travelled from the point of origin to the point of consumption (Pirog and Benjamin, 2003). A measure of food miles, the Weighted Average Source Distance (WASD), was developed by Annika Carlsson-Kanyama (Carlsson-Kanyama, 1997). The following equation was used to calculate the average source distance:

$$\text{WASD} = \frac{\sum(m(k) * d(k))}{\sum m(k)}$$

Where:
k = location points of product origin
m = weight or amount from each point of origin
d = distance from each point of origin to point of purchase

Carlsson-Kanyama (1997) calculated the WASD for tomatoes and carrots consumed in Sweden in 1992. The WASD measure has been used in studies by the Leopold Center for Sustainable Agriculture to measure changes in distance travelled for grapes consumed in Iowa for three different years and the distance travelled by 16 different produce items sourced locally and from conventional sources (Pirog et al., 2001; Pirog and Benjamin, 2003).

Lack of detailed route information can limit the accuracy of the Weighted Average Source Distance measure (Carlsson-Kanyama, 1997). In studies using the WASD measure, the actual route a food product travelled was unknown; therefore, the distance calculated as the WASD was not exact (Carlsson-Kanyama, 1997; Pirog et al., 2001; Pirog and Benjamin, 2003; Wallgren, 2006). Distances were measured using a straight line between the source point and consumption point or using Internet sources such as Mapquest to calculate distance along roads (Carlsson-Kanyama, 1997; Pirog et al., 2001; Pirog and Benjamin, 2003; Wallgren, 2006).

In addition to not knowing the exact travel route, the exact location of the point of origin was often unknown and was generalized for WASD analysis. Methods for identifying the source point included using the city closest to the center of the state of origin and placing source points in areas of production (Carlsson-Kanyama, 1997; Pirog and Benjamin, 2003).

A simple WASD measure does not consider the mode of transportation (Carlsson-Kanyama, 1997). Differences between energy use and greenhouse gas emissions between truck, rail, ship, and air can be substantial (Wallgren, 2006). According to Pirog et al. (2001), food could be transported seven times as far by ship as by truck and not use a greater amount of energy or emit more greenhouse gases. Meisterling et al. (2009) found the global warming potential of wheat changes substantially depending on whether it is shipped by truck or by rail. After considering energy use of transportation modes, Wallgren (2006) concluded local food systems do not necessarily use less energy than conventional food systems.

Increased Imports

A significant change in food distribution has been the increase in imports to the United States (Weber and Matthews, 2008). Annual imports of fresh fruit and vegetables to the United States increased by $5.2 billion from 1990-92 to 2004-06 (Huang and Huang, 2007). Huang and Huang attribute part of the increase in imports to a greater demand for a variety of fruits and vegetables year-round, technological innovations that maintain food quality during transport, and the North American Free Trade Act (NAFTA). NAFTA went into effect in 1994, and fresh fruit and vegetable imports from Mexico and Canada increased from $1.12 billion to $4.3 billion between 1990-02 and 2004-06 (Huang and Huang).

Purpose

Growing concerns about energy use and greenhouse gas emissions combined with growing interest in eating ‘locally’ has led to efforts to quantify food transportation. A simple measure of the distance a food product has travelled can provide an indication of its energy requirement for transportation, but the distance is often based on incomplete knowledge about transportation routes and fails to consider the mode of transportation. Changes in how food is distributed, especially the increasing amount of imports to the United States, can impact transportation distance, energy use, and environmental cost (Hendrickson, 1994). In an effort to explore the impact of imported food and the relationships between distance travelled, energy use, and emissions, this study analyzed 2008 import data for three popular food items. A geographic information system was utilized for generating realistic travel routes.

Product Choice

Apples, oranges, and bananas were chosen for this study because of their popularity in the United States. According to Pirog and Tyndall (1999), the average consumer in the United States consumed 47.1 pounds of fresh or processed apples in 1998. No other fruit was consumed in as large of a quantity (Pirog and Tyndall, 1999). An analysis by the United States Department of Agriculture Economic Research Service found apples, bananas, and oranges ranked one, two, and three, respectfully, for number of fresh and processed servings purchased in 1999 (Reed, Frazao, and Itskowitz, 2004). Apples, bananas, and oranges were also found to be the top three fresh and processed fruit for millions of pounds purchased (Reed et al., 2004).

Methods

Import data for apples, oranges, and bananas were obtained from the United States Department of Agriculture’s (USDA) Fruit and Vegetable Market News website for each month in the year 2008 (USDA, 2009). This data included the produce type, country of origin, month, the point of entry in the United States, the number of 10,000 pound units in the shipment, and the mode of transportation. Software programs used for analysis were Microsoft Excel and ESRI ArcGIS 9.2 including the Spatial Analyst, Network Analyst, and Military Analyst extensions. All tools referred to in the methods are ArcGIS tools.

Creating Routes and Measuring Distance

The distance of each shipment was needed to calculate the energy and environmental cost of each produce shipment. There were three modes of transportation: boat, air, and truck. Separate routes were created for each mode of transportation from source country to point of entry in the United States.

Point of Origin

Import data from the United States Department of Agriculture's Fruit and Vegetable Market News website included the country of origin but not the place of origin within the country. A method for determining an appropriate point of origin within the country of origin was needed. An assumption was made that the shipment would originate close to where the commodity was grown in the country of origin.

For each produce type, 2 datasets in ArcGIS ASCII format in latitude by longitude at 5 minute resolution were retrieved from the website of the Department of Geography at McGill University in Montreal, Quebec and converted to ArcGIS raster format using the WGS84 datum (McGill University, 2008; Monfreda, Ramankutty, and Foley, 2008; Ramankutty, 2009). The cell value of one raster indicated the proportion of the cell area harvested. The second raster indicated the yield in tons per hectare. These rasters were multiplied to create a raster indicating the amount grown per cell. From this point forward, this raster layer will be referred to as the 'harvest raster'.

The harvest rasters were extracted for each country of origin and projected into a continental equidistant conic projection for the country (e.g. South America Equidistant Conic for Argentina). An appropriate geographic transformation was applied as needed.

For each country of origin, the weighted mean center of the harvest region was calculated using the Mean Center tool. The input for the Mean Center tool was a point layer converted from the projected harvest raster using the Raster to Point tool. The points were weighted according to the cell values of the original harvest raster. The closest port and airport to the mean center were found using the Spatial Join tool for boat and air routes, respectfully (Figure 1).

ArcGIS Model Builder was used to create a model to replicate this process for each country and output a shapefile with the port or airport of origin. For countries of origin in Central America, a port for each coast was determined so that shipments destined for the east coast of the United States would leave from the east coast of the country of origin and the west coast destinations from the west coast. This was assumed to be the more likely scenario compared to boats making a significant detour south through the Panama Canal to reach the opposite coast.

A variation of this method was used to determine the Canadian boat shipment source port for apples, which will be explained in the Truck Routes section to follow. There were two banana source countries, Nicaragua and Peru, where the growing area and yield data were insufficient for determining the harvest raster. In these cases, the port or airport closest to the center of the country was used as the source point.

Air Routes

A shapefile of world airports was obtained from the Pacific Disaster Center website (Pacific Disaster Center, 2002). A similar source was used by Weber and Matthews (2008) for their study. The airport closest to the weighted mean center of the growing region and the destination airport were identified. If the point of entry in the USDA import data did not include the name of the airport, the main international airport in the city of entry was used (e.g. Phoenix Sky Harbor International Airport for Phoenix).

The latitude and longitude of each airport was obtained, and the great circle distance and bearing between the source airport and point of entry airport were calculated using an Excel spreadsheet with equations from Veness (2002-2009). A table with the source airport, distance, and bearing were converted to a shapefile using the Military Analyst Table to GeodesyLine tool. The distances in kilometers between the source and destination airports calculated in Excel were used for the route distance attribute of the air routes.

Boat Routes

Attempts were made to create shortest routes by water for boat shipments, but the results were affected by multiple sources of error. To provide a better estimate of distance, the document *Distances Between Ports* was obtained which includes distances between ports and junction points (National Imagery and Mapping Agency, 2001). This source was also used by Weber and Matthews (2008) when calculating import distances. Most distances listed measure the shortest navigable route between points, but some distances are longer to benefit from currents, avoid ice and other dangers, or conform to traffic regulations (National Imagery and Mapping Agency, 2001).

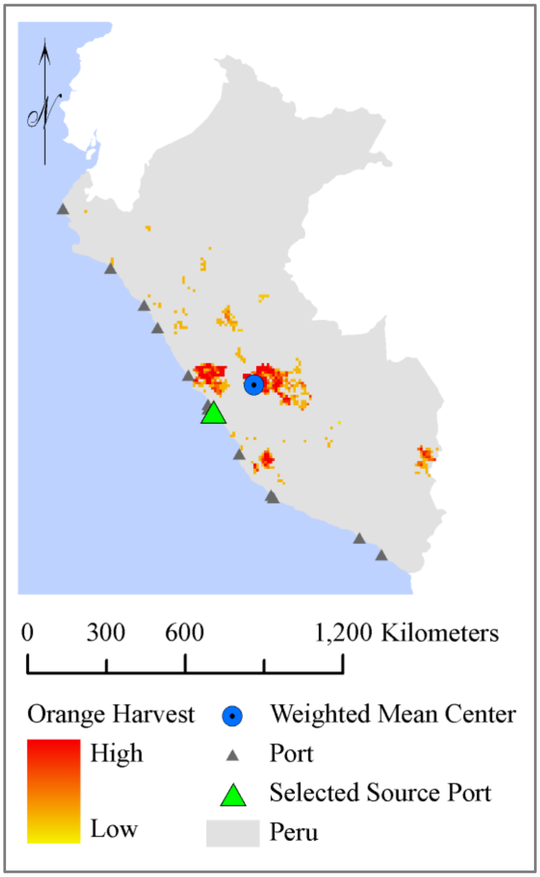


Figure 1. Example of source port selection for oranges imported from Peru by boat. The selected port (green diamond) was the closest port to the weighted mean center (blue circle) of the growing region (yellow to red).

The document includes latitude and longitude for ports and junction points. Junction points are defined as “a position where many routes converge and through which ships pass when sailing from one major area into another (National

Imagery and Mapping Agency, 2001)." Each port listed in the document for each country of origin was mapped using the listed latitude and longitude. These points were used when determining the closest port to the weighted mean center of the growing region previously described.

The latitude and longitude of each source port, point of entry port, and any appropriate junction points were obtained from the *Distances Between Ports* document. Some ports of entry listed in the import data were not in the document. These were located using the World Port Index shapefile and the closest port listed in *Distances Between Ports* was used (National Geospatial-Intelligence Agency, 2005). In some cases the port to port distance was not included in the document. For these routes the distances were estimated using nearby ports or using appropriate ports in between the source port and destination port as junctions. If a port was within five miles of another port it was considered acceptable to substitute the distance to the nearby port as its own. The previously described Excel calculations were used to find the great circle distance and bearing for each route segment (Veness, 2002-2009).

These route segments were represented visually by importing the distance and bearing data using the Military Analyst Table to GeodesyLine tool. Although the resulting map shows a great circle shortest line for each segment, the distance used for final calculations is the more realistic ship distance from the document, not the length of the great circle line. The great circle line segments show the ports and junctions used when determining the distance of the entire route. The route segments shapefile was dissolved into single route features incorporating each corresponding route segment and summing the corresponding segment distances.

Truck Routes

Each produce type included some shipments from Canada or Mexico. The Oak Ridge National Highway Network dataset was used for route analysis (Oak Ridge National Laboratory, 2008). The geography and distribution of growing regions in each country necessitated developing separate routing methods. The apple growing regions were distributed across the southern portion of the Canada from east to west. The points of entry for apples were also distributed along the border between Canada and the United States. An assumption was made that apple shipments would be routed from the growing regions to their closest point of entry. The apple harvest raster was converted to points including the harvest cell value as an attribute. The points were spatially joined to the nearest point of entry in the United States. Those points closest to Elizabeth, New Jersey, the only boat point of entry in the United States for apple shipments arriving from Canada, were used to determine the source port for this boat route.

The remaining points were spatially joined to the nearest highway network junction. The junctions were given an attribute with the sum of the grow region harvest point values joined to them. The Network Analyst Closest Facility tool was used to create paths from each junction to the nearest point of entry (Figure 2).

For each point of entry the average distance from the junctions closest to that point was calculated. This average distance was weighted by the grow region harvest values so that a route from a high apple harvest area would affect the average distance more than a route from a low apple harvest region. All routes from grow region junctions to points of entry are depicted as the 'apple routes', but the route distance used for analysis is the average distance described above.

For one point of entry in Pembina, North Dakota, there were no grow regions in Canada closest to it. For this route, the shortest path from the closest major city (Winnipeg, Manitoba) was used.

The growing regions for bananas and oranges in Mexico were concentrated in the southern portions of the country. The shape of the country created a situation where all grow region points were closest to one point of entry. For this reason, the method of routing the grow region junctions to their closest point of entry was not applicable. Instead, the weighted mean center of the grow region was determined. The closest junction to this point was found using a spatial join. Routes were created to each point of entry from the weighted mean center closest junction. Distances were determined from the total miles calculated from the highway network and converted to kilometers.

There were two anomalies in the points of entry listed in the Import data for Mexico. The majority of points of entry listed were cities on the border of Mexico and the United States; however, one point of entry was listed as Blaine, Washington and a second was listed as Texas without a particular city specified. To standardize the routes as routes from the point of origin to the point of entry to the United States, points on the Mexico border were estimated for these two cases. The shortest path using the highway network from the growing region weighted mean center to Blaine, Washington and the center of the state of Texas were created using Network Analyst. The city where each route crossed the Mexico–United States border was used as the point of entry.

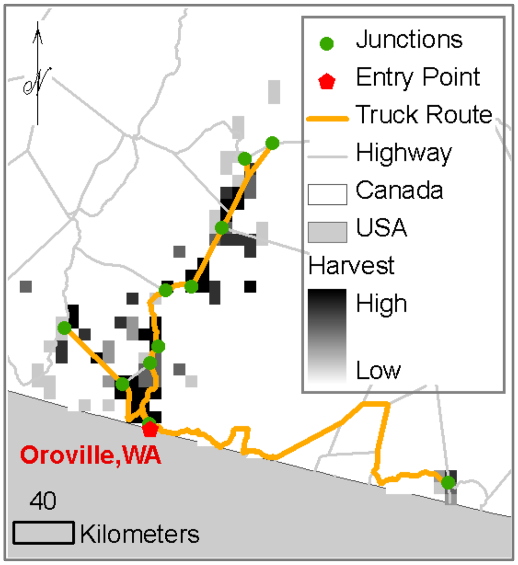


Figure 2. Truck routes from apple harvest area junctions in Canada closest to Oroville, Washington.

Import Mode

For five banana routes and three apples routes, "Import" appeared as the mode of transportation. This occurs when the shipment crossed from a country other than the country of origin (Maxwell, 2009). In each case, the destination point of entry was near the Canadian-United States border, so it was assumed the produce arrived in Canada from the country of origin and then crossed into the United States. The route was created from the country of origin to the nearest Canadian port or airport to the US point of entry listed in the import data.

A mode of transportation still needed to be determined. In each case the mode was assumed to be the same mode as the majority of the shipments from the country of origin. The route segment from the Canadian point of entry to the United

States point of entry was left unaccounted for. It was assumed to be small and assigning multiple modes of transportation to a single shipment route would have introduced challenges when accounting for energy and greenhouse gas emissions.

Final Route Layer

All shipping routes were merged into a shipping route vector data layer. The routes included an attribute of distance measured in kilometers and a route identification attribute that indicated the produce type, transportation mode, source country, and point of entry.

Joining Import Data to Routes

Multiple shipments along each route in 2008 necessitated a one-to-many route to shipment join. This was accomplished using the Make Query Table tool. The resulting table had a route feature for each imported shipment.

Each shipping route feature included an attribute for the tons of produce transported and the route distance. These two attributes were multiplied to calculate a new ton-kilometer measure for each shipment.

Energy and Environmental Factors

In order to compute energy use and environmental cost, energy use and greenhouse gas emissions for each mode of transportation were obtained (Table 1). A table was created listing energy and greenhouse gas emissions per ton-kilometer for each transportation mode (Weber and Matthews, 2008). This table was joined to the shipping layer, and total energy and greenhouse gas emissions for each shipping route were calculated.

The following statistics were computed: total tons imported, annual and monthly weighted average source distance, total energy use, annual and monthly energy/ton, total emissions, and annual and monthly emissions/ton. The weighted average source distance method developed by Carlsson-Kanyama (1997) was used to calculate the average distance travelled.

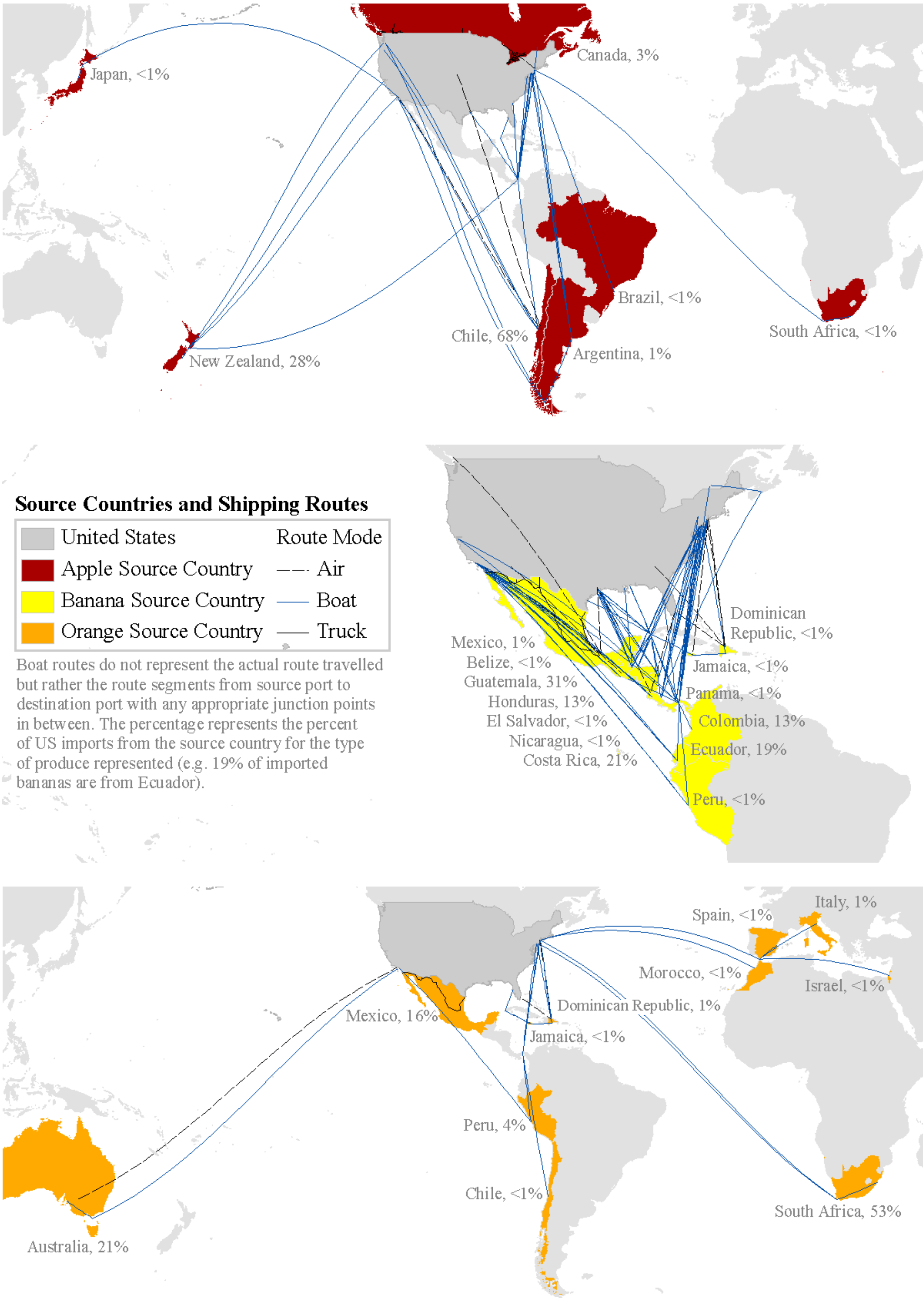
Table 1. Energy (MJ/t-km) and emissions (tCo_2e/t-km x 10^6) factors for air, boat, and truck shipments This table was adapted from Weber and Matthews (2008) which cited: *Transportation Energy Data Book: Edition 26* (2007) by S.C. Davis and S.W. Diegel; *Development and Applications of GREET 2.7 – The Transportation Vehicle-Cycle Model* (2006) by A. Burnham, M. Wang, and Y. Wu; Environmental assessment of freight transportation in the U.S. (2006) by C. Facanha and A. Horvath; and Updated Emissions from Ocean Shipping (2003) by J.J. Corbett and H.W. Koehler.

Mode	**MJ/t-km**	**t CO_2e/t-km x 10^6**
Air	10.0	680
Boat	0.2	14
Truck	2.7	180

Results

Routes were mapped for all apple, banana, and orange shipments (Figure 3). There were 160 total routes including 36 apple routes from seven countries, 101 banana routes from 13 countries, and 23 orange routes from 11 countries. The percentage of each transportation mode used is shown in Table 2.

Bananas were imported in much larger quantities than apples or oranges (Table 3), which is also indicated by much higher total energy and emissions. The results indicate that out of imported apples, bananas, and oranges, bananas had the lowest annual weighted average source distance, energy expenditure per ton, and



Boat routes do not represent the actual route travelled but rather the route segments from source port to destination port with any appropriate junction points in between. The percentage represents the percent of US imports from the source country for the type of produce represented (e.g. 19% of imported bananas are from Ecuador).

Figure 3. Shipping routes for 2008 apple (top), banana (middle) and orange (orange) imports.

Table 2. Percent of tons shipped per transportation mode per type of produce.

	Air	Boat	Truck
Apples	0.55%	96.53%	2.92%
Bananas	0.01%	98.61%	1.38%
Oranges	0.01%	83.62%	16.37%

Table 3. Total tons, energy, and emissions for 2008 imports.

	Tons	Energy (MJ)	Emissions (Tons CO_2e)
Apples	156,936	403,396,833	28,077
Bananas	4,591,851	3,554,803,890	247,496
Oranges	109,332	320,265,440	22,168

emissions per ton (Figure 4). Apples and oranges were closer in each annual measure, but oranges had the highest value for each.

The weighted average source distance, average energy expenditure, and average emissions for bananas were found to be fairly consistent throughout the year (Figure 5). Apples and oranges displayed more variability. The weighted average source distance peaked in June for apples and October for oranges.

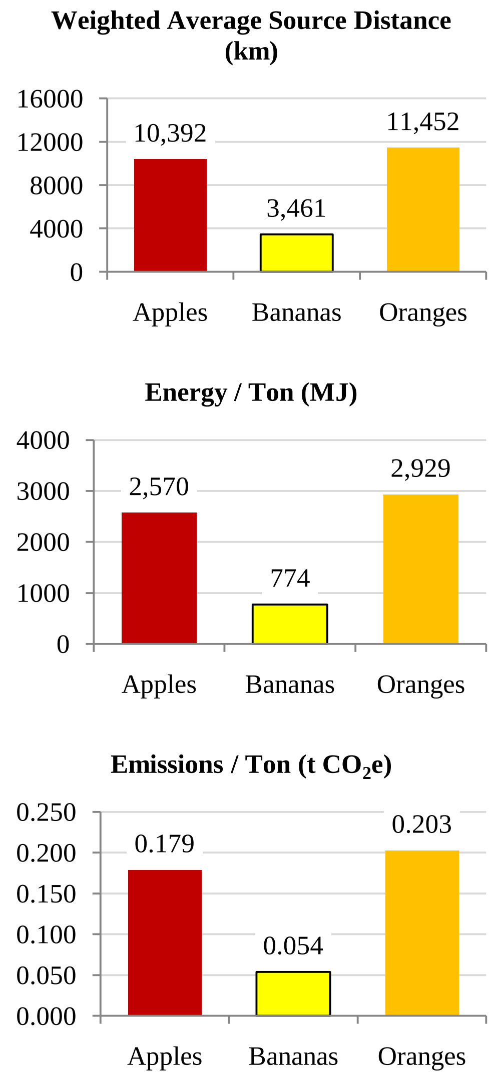


Figure 4. Annual weighted average source distance, energy/ton, and emissions/ton.

Discussion

The purpose of this study was to compare apple, banana, and orange imports in terms of distance, energy, and emissions for the year 2008. A secondary interest was to assess how well the weighted average source distance measure is correlated with average energy and emissions.

When viewing the results, it is important to remember only imports of apples, bananas, and oranges were analyzed. Shipments within the United States from domestic growing regions or from import points of entry to points of consumption were not included. Routes were only analyzed to the United States point of entry.

All banana shipments listed in the USDA 2008 monthly movement reports were imports from other countries. This is not the case for apples and oranges. The domestic sources of apples and oranges

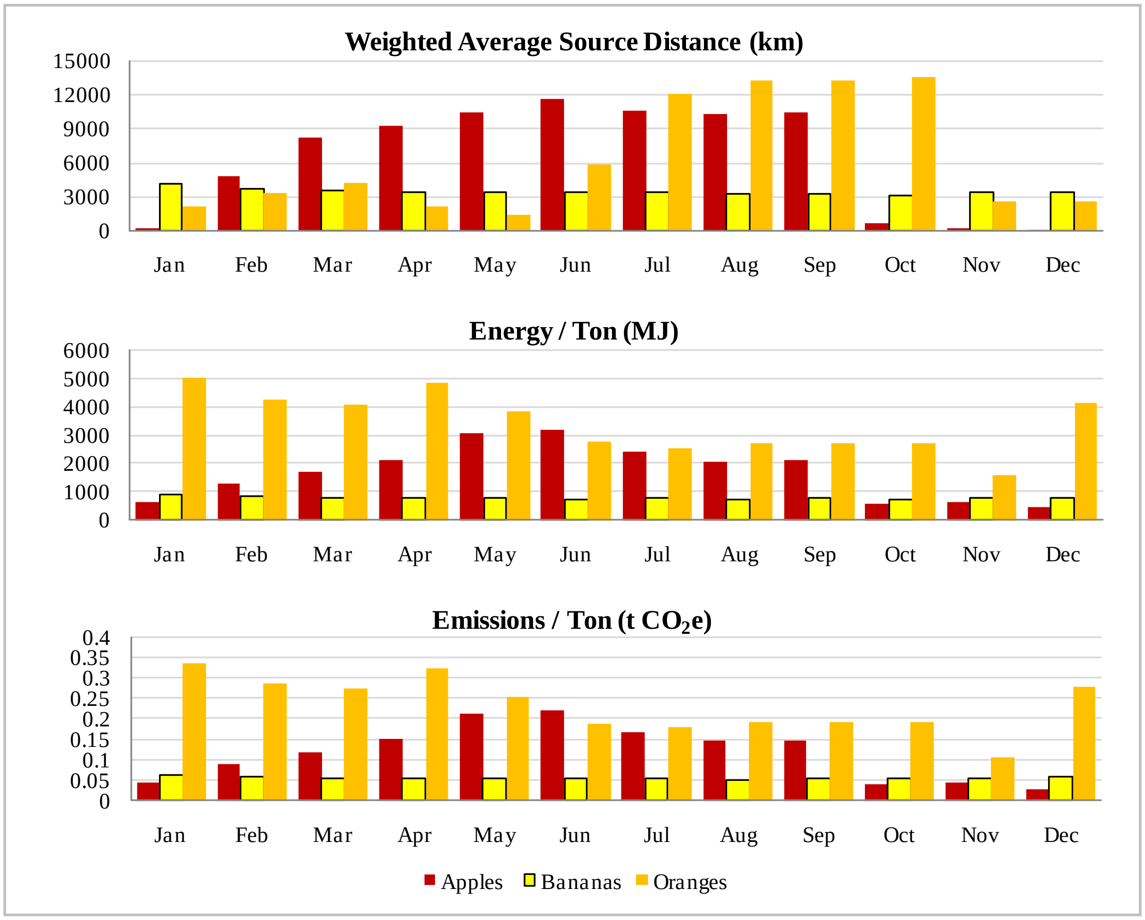


Figure 5. Monthly weighted average source distance, energy/ton, and emissions/ton for apples (red), bananas (yellow), and oranges (orange).

also have transportation energy and emissions that are unaccounted for in this study; therefore, the total tons, energy, and emissions reported in the results should not be used to draw conclusions on the overall impact of apples, oranges, and bananas.

WASD vs. Energy vs. Emissions

If only annual summary statistics are viewed, one may conclude that the weighted average source distance is a good indicator of energy expenditure and emissions (Figure 6). This is probably due to the relatively similar distribution of transportation modes among the three types of fruit. Air transportation, which would have a large affect on average energy and emissions, was used in less than one percent of shipments for each type of fruit. Truck was used as the mode of transportation for about 16% of orange shipments, compared to less than 3% for apples and bananas, but this difference does not appear to substantially alter the relationship between average distance and energy or emissions over the course of a year.

The annual statistics mask the variability between various route and mode combinations. This variability becomes more apparent when the metrics are calculated on smaller monthly subsets of data. The correlation between distance and energy and distance and emissions becomes especially weak for oranges. This is the only item of the three analyzed where more than 4% of the shipments used a mode of transportation other than boat.

Sources of Error

Although effort was made to calculate the most realistic route distances, the generated routes are a generalization. Much is left unknown about the exact routes travelled by each shipment. The distances calculated were meant to be a conservative measurement following the shortest realistic route. Stops for loading and offloading other goods, refueling, and other reasons are unknown.

There were additional sources of uncertainty in the import data from the USDA. In less than one percent of the shipment records, the mode was unknown because the shipment arrived from a country other than the country of origin. Assumptions were made to assign a mode to these shipments that could be unfounded. Another uncertainty is due to

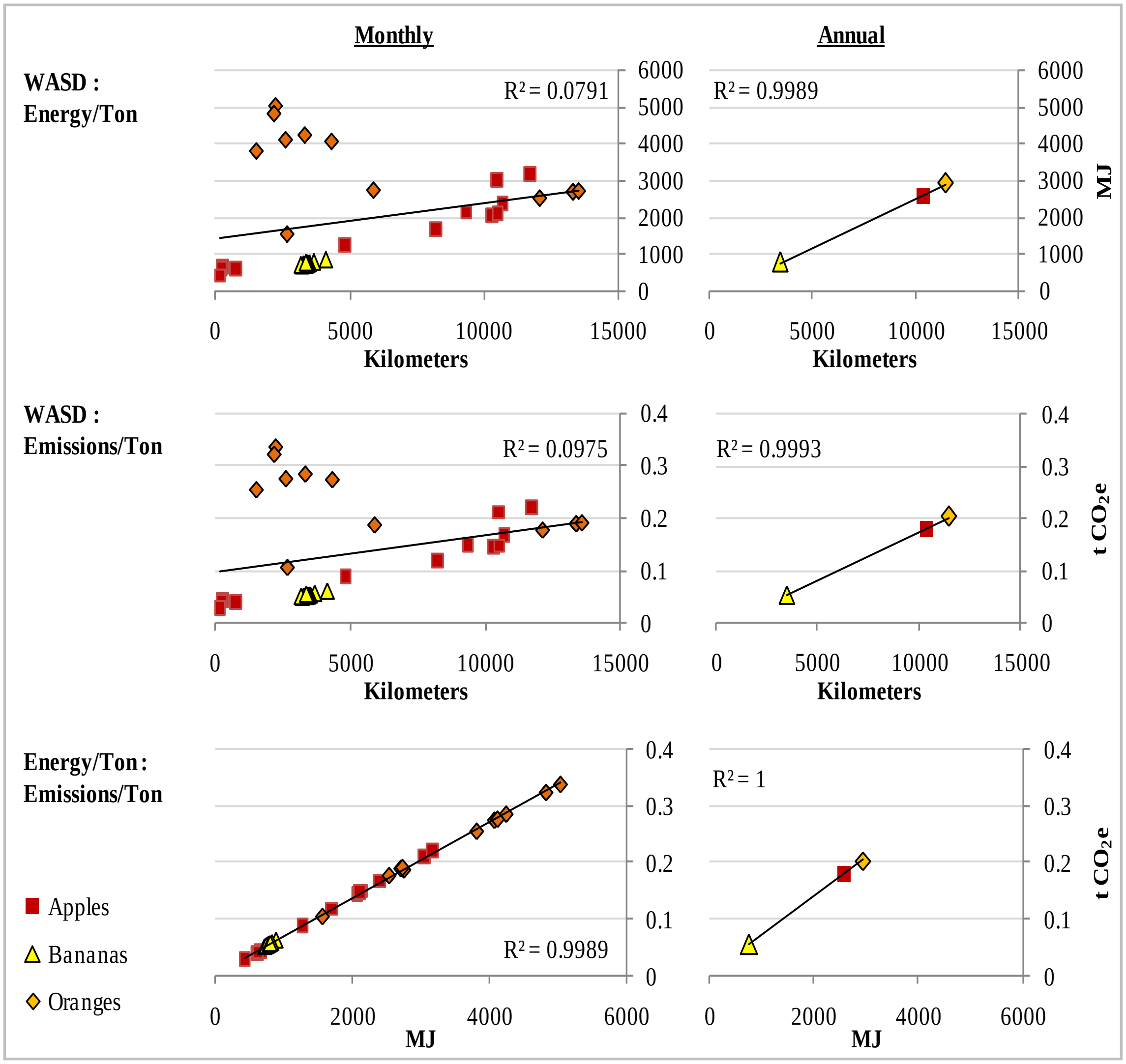


Figure 6. Monthly and annual plots and R-squared values comparing measures of weighted average source distance, energy/ton, and emissions/ton.

the quantity unit used in the import reports. The data are reported in 10,000 pound units (5 tons). For approximately 3.5% of the shipments, the number of 10,000 pound units recorded was ‘0’. Instead of deleting these shipments all together, one ton was substituted for the quantity. In reality this number could be anything less than five tons.

Any estimate of energy expenditure and emissions per ton-kilometer is subject to error. Both estimates can change significantly due to many factors including the size of the ship, plane, or truck, the type of fuel, and whether or not climate controlled storage is used. For example, fuel consumption can vary from 25 to 55 liters per 100 km depending on the size of truck and presence or absence of a trailer (Wallgren, 2006).

Context

Travel distance and mode of transportation are not the only variables that affect the environmental impact of a food product (Carlsson-Kanyama, 1997; Pretty, Ball, Lang, and Morison, 2005). Changes in production practices and consumption patterns can have an equal or greater impact on energy use and greenhouse gas emissions compared to shortening the transportation distance (Weber and Matthews, 2008).

Food transportation is often studied as a component of a larger life cycle assessment (Weber and Matthews, 2008; Meisterling et al., 2009). A life cycle assessment measures the total environmental impact of a product from the time it is created to the time it is disposed of (Pirog et al., 2001). The large scope of these studies sometimes leads to combining various food items into groups for analysis (Weber and Matthews, 2008). The methods used in this study could provide a more detailed transportation analysis for individual products.

Recommendations for Future Work

The methods used and system developed could be adapted by researchers to analyze other imported products or to model hypothetical transportation scenarios. This could benefit policy makers concerned with reducing energy use and greenhouse gas emissions. An additional domestic network could be added which would allow calculations from any source point to any location in the United States.

Conclusion

A geographic information system was found to be a useful tool for generating routes, analyzing import data, and communicating results visually. Quantity, distance, and transportation mode should all be considered when assessing the environmental impact of transporting food. Much additional research is needed to understand the full cost of producing and transporting food. A geographic information system and the methodology presented could be used in the future to analyze additional products and model changes in source countries and transportation modes.

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