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Estimating the Blue Water Footprint of In-Field Crop Losses: A Case Study of U.S. Potato Cultivation

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Abstract: Given the high proportion of water consumption for agriculture, as well as the relatively common occurrence of crop losses in the field, we estimate the amount of water embedded in crops left on the farm. We are particularly interested in understanding losses associated with fruits and vegetables, having a higher level of harvesting selectivity and perishability (and thus, losses) than grain crops. We further refined the study to focus on potatoes, as they represent the largest acreage under cultivation of all fruit and vegetable crops in the U.S. We attempt to get the most complete understanding of pre-harvest and harvest loss data for potatoes by leveraging three centralized data sets collected and managed by the United States Department of Agriculture (USDA). By integrating these three distinct data sets for the five-year period 2012–2016, we are able to estimate water consumption for potato cultivation for total in-field losses by production stage and driver of loss for seven major potato-producing states (representing 77% of total U.S. potato production). Our results suggest that 3.6%–17.9% of potatoes are lost in the field with a total estimated blue water footprint of approximately 84.6 million cubic meters. We also find that the leading driver for crop loss for in-field potato production is harvest sorting and grading, accounting for 84% of total lost production at the farm. We conclude with a discussion of opportunities for improved national level data collection to provide a better understanding of in-field crop losses over time and the resource footprints of these losses.

Keywords: food loss; food waste; water footprint; agriculture; supply chain

1. Introduction

Approximately 96 billion gallons of water per day (bgd) (~0.36 cubic kilometers) are consumed for agricultural irrigation in the United States, representing roughly 83% of total national water consumption (116 bgd or 0.42 cubic kilometers) across all end-use categories [1]. Meanwhile, it is estimated that around 40% of food produced in the U.S. is lost or wasted at some point along the supply chain [2]. Combining these two observations together suggests that more than 30% of all the water consumed in the U.S. is ultimately wasted as the water embedded in food products that go uneaten.

Studies seeking to quantify and characterize the amount of food loss and waste (FLW) at various stages of the food supply chain have been increasing in recent years [3]. Part of the momentum behind these studies is the growing recognition that FLW represents significant economic losses, as well as the inefficient allocation of resources (land, water, energy, fertilizers, and other material inputs) to produce food that is never consumed by humans [4]. One of the challenges to researchers in this topic area is applying a consistent definition of food loss and waste. Some researchers suggest that food waste should only be defined as the material that ends up in a landfill where it has zero productive value [5], while others take a broader definition to include all edible food that is intended for human consumption but ultimately does not get eaten [6]. "Food loss" and "food waste" are often further distinguished from each other, where "food loss" may refer to only upstream losses in the supply chain, from production to delivery to the retailer, while "food waste" refers to food discarded at retail through the point of consumption (e.g., homes, restaurants, and institutions) [7].

Despite the growing number of FLW studies, estimating food losses in agricultural production remains a significant challenge as losses vary significantly by crop type and from season to season [8,9]. There are four main drivers of crop loss in the field: weather damage, disease and pests, market conditions, and grading/sorting of produce to meet buyer standards. Weather damage can occur as a result of extremes in temperature (both heatwaves and frost/freezing), precipitation (e.g., drought, excess moisture, flooding, and hail/snow), and other extreme events (e.g., hurricane, fire, lightning) [10]. Disease and pests include various forms of plant disease, including fungal infections [10], as well as damage by insects, rodents, birds, and other pests [7,11]. Market conditions can prevent the harvest of entire crop areas if the crop price falls below harvesting costs, the grower is unable to secure adequate labor for harvest, or the downstream buyer changes or cancels an order [9,11]. Finally, during harvest, a significant volume of product may be culled or out-graded to improve the overall quality of the product (size, shape, color, etc.), as well as increase the probability that it will actually reach its intended market in terms of ripeness and perishability [11].

The relationship between FLW and the upstream water inputs for food production can be conceptualized as the "water footprint" of FLW. The water footprint, developed by Hoekstra and Chapagain [12], is a mature indicator in the field and has been applied to assess and compare the amount of water embedded in the goods and services produced and consumed by society. The water footprint concept includes three categories of water use: "blue" water representing the use of surface and ground water, "green" water representing the direct utilization of rain water by land-based ecosystems (including rain-fed agriculture), and "gray" water representing the amount of water required to sufficiently dilute pollutants before release into the environment [13].

A number of studies have estimated water footprints for geographic regions of varying scales, including global studies [14], large regional studies (e.g., the European Union [15]), national studies (e.g., Morocco [16]), as well as urban systems (e.g., an analysis of 65 cities and metropolitan areas [17]). Other studies have explored individual economic sectors, e.g., bioenergy [18], tourism [19], and agricultural products [20]; specific institutions, e.g., the Barilla food company [21] and the exchange-listed companies in the Netherlands by [22]; as well as single products, e.g., meat products [23] and even a very specific Brazilian soap bar [24].

The water footprint approach has been applied specifically to FLW in a number of recent reports and papers. In 2012, Kummu et al. [25] estimated the global blue water footprint of FLW to be approximately 46 trillion gallons (~174 cubic kilometers) per year, representing about 24% of the total water used for global food production. On a per unit basis, a collaborative study between the Waste and Resources Action Programme (WRAP) and the World Wide Fund for Nature (WWF-UK) estimated that 750 cubic meters (~198,000 gallons) of water is wasted per metric ton of avoidable food waste in the United Kingdom [26]. A large-scale study of consumer food waste in the European Union (EU) estimated the per capita blue water footprint of food waste to be 27 L per day (~7.1 gallons/day) [27].

In terms of FLW and global agricultural production, roughly 22% of produced cereals, 39% of fruits and vegetables, and 33% of roots and tubers are lost across various stages of the food supply chain, including consumption [25]. Based on this data, our team narrowed our focus on the higher loss categories of fruits/vegetables as opposed to cereal crops. We further narrowed the focus to potatoes specifically, since it is the largest fruit/vegetable crop by acreage in the United States [28]. Potatoes also had the greatest breadth and depth of data available from the three national-level data sets on pre-harvest crop loss that we identified, the United States Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) Census of Agriculture [29] and Survey Program [30], and the USDA Risk Management Agency (RMA) [10]. Estimates of in-field potato losses at harvest were collected from the NASS Objective Yield (OY) survey [31]. After reviewing and consolidating all of the in-field loss data, we estimate the blue water footprint of the potato losses in the United States using state-specific estimates of irrigated water application from the NASS Farm and Ranch Irrigation Survey (FRIS) [32]. These data sources are described in further detail in the Materials and Methods section below.

2. Materials and Methods

This study seeks to estimate the blue water footprint of potato losses in the United States during the agricultural production stage of the potato supply chain. We consolidated pre-harvest and harvest potato loss data from both USDA NASS and RMA data sets to estimate losses by loss driver and by state. We then apply water irrigation estimates to the estimate of total losses from these combined datasets to calculate the blue water footprint of in-field losses.

2.1. System Boundary and Definitions

We focus the first part of our study on pre-harvest potato "losses", defined as potatoes cultivated for human consumption that were abandoned during the growing process as a result of weather, pests/disease, and/or market conditions. Following pre-harvest losses, we also include potatoes lost at the harvest stage where they are left in the field for being too small or just missed in the mechanical harvesting process. This would include potatoes that fall out of the harvester, fall through sorting chains, or are incorrectly sorted by the harvester. We also exclude "seed potatoes" in-field loss estimates because they are cultivated only for future potato cultivation and not human consumption. In estimating the water footprint of the in-field potato losses, we focus specifically on the blue water footprint to narrow the system boundary to water extraction for irrigation directly from surface and groundwater sources, similar to the approach by Kummu et al. [25].

2.2. Data Sources and Limitations

We rely on two separate sources of data to estimate pre-harvest potato losses in U.S. agricultural production: the USDA NASS survey data set that collects a range of agricultural production data by crop type and U.S. county [33], and the USDA RMA data set that consolidates crop loss data from crop insurance claims, also specified by crop type and county [10]. Each of these data sources includes an estimate of pre-harvest losses allowing for comparison across sources. We rely on additional data sets from NASS for our estimates of potato losses at harvest (for selected states) [31] and quantity of water-applied per irrigated acre of potato production in the U.S. [32]. By linking all this data together, we are able to derive the blue water footprint embedded in the pre-harvest and harvest potato losses for seven major potato-producing states. Each of these key data sources is described in detail in the following sections.

2.2.1. USDA NASS Survey Data

The USDA NASS collects agricultural data via a yearly survey [30] and a 5-year census [29]. Both the survey and the census have a long legacy stretching back into the early 1900s and present a detailed record of historical agricultural production across the United States. For most crops, the NASS survey data is reported at both the county and state levels. The survey data is collected via a questionnaire sent to farmers to self-report estimates of their production. The census, on the other hand, sends enumerators to farms across the country to physically collect information on farm production.

A key initial step in reviewing the NASS data was to assess data availability for potatoes. Likely a result of it being the largest fruit/vegetable crop in the U.S., potatoes proved to have robust data coverage (in terms of number of data variables and data consistency from year to year) within the fresh produce census and survey data collected by NASS. The survey data collected include the following variables relevant to this study: Acres Harvested, Acres Planted, and Yield/Acre. Data for each of these variables are available on a yearly basis and reported at both the county and state levels. Unfortunately, these three variables are not available for all crops covered by the NASS survey (e.g., tomatoes, apples, and head lettuce), so our approach for estimating pre-harvest potato losses is not necessarily immediately transferable to other crops.

A potential limitation to the NASS survey data is the problem of self-reporting. Since the survey is conducted by sending questionnaires to producers and having them voluntarily respond, we expect some inaccuracies in responses. The sample size and accuracy of the survey is mostly up to producers. For the NASS census, the deployment of external evaluators has the potential to be more accurate than the survey. However, no direct estimates of loss can be derived from this parallel data source because NASS does not collect data on "acres planted" during the census (only "acres harvested").

Despite relatively robust coverage overall, some gaps remain in the NASS survey data. In terms of spatial coverage, data for counties with only a single producer are omitted from the database to address privacy concerns. This is an understandable approach, but it does limit the value of the county-level data by preventing full-coverage comparisons between counties as well as the aggregation of the county data. However, the state figures do aggregate these single producer counties into their total. This then accounts for what would be missing values in the county figures. Another concern with using county level data is that over the course of our period of interest, the number of reporting counties decreased significantly. We would then be left with an unbalanced panel, either skewing our results or forcing us to ignore valuable data. Thus, for the purposes of our study, we relied solely on the state-level data. While the state-level aggregation limits more detailed assessment of the blue water footprint of potato losses on water scarcity and other more spatially granular issues (e.g., water pollution, land use, and local economy), we believe it is a necessary adjustment to match the resolution of the water footprint analysis to that of the available (and most complete) data.

Leveraging the key variables available from the NASS survey [33], we estimate state by state agricultural potato losses for the five-year period, 2012 to 2016. We restrict our attention to the 2012–2016 range to better represent current agricultural practices, as well as to align the data with the relevant timeframe for the NASS OY harvest loss data (described in the following section). Pre-harvest losses were calculated using the following Equation (1):

$$PL_s = (AP_s - AH_s) \times Y_s \tag{1}$$

where,

PL_s = Average pre-harvest agricultural potato losses (tonnes) based on NASS loss estimate by state (s), 2012–2016
AP_s = Acres planted estimate from NASS by state (s), average value 2012–2016
AH_s = Acres harvested estimate from NASS by state (s), average value 2012–2016
Y_s = Yield per acre estimate from NASS by state (s), average value 2012–2016

While the NASS data provide a high-level view of losses on the farm in terms of the acres of crops not harvested, they provide no information about why the losses occurred, e.g., drought, frost, or market conditions. Further, the NASS survey does not include any information about in-field losses that occur during the harvesting process. To include these two components in our study, we had to integrate additional data sets described in the following sections.

2.2.2. USDA RMA Data

The USDA RMA publishes a yearly "Cause of Loss" dataset, which tracks information on crop insurance claims [10]. This data records the size (in acreage), monetary value, and type of loss for each insurance claim made to the organization. The agency only began to record estimates of acreage losses in 2001. From 1989–2000 they only recorded dollar-value indemnities, which is difficult to translate back into a physical quantity based on changing market prices as well as the heterogeneity of the individual insurance agreements. For the purpose of our study, we utilize data from 2012 to 2016 to align with the data availability for the harvest loss data (next section).

The RMA dataset is unique as it provides information not just on the amount of losses but also the drivers (i.e., "damage types") and stages of the losses over time and by region. Figure 1 provides a summary of the total RMA indemnification data for potatoes by damage type. The figure summarizes this data going back to 2001 in order to give some historical context for these losses. As shown, the leading damage type driving potato losses is the category of "excess moisture, precipitation, and rain" at more than $300 million over the 16-year time period, 2001 to 2016. This is more than the following five damage type categories (heat, plant disease, failure in irrigation supply, hail, and freeze) combined.

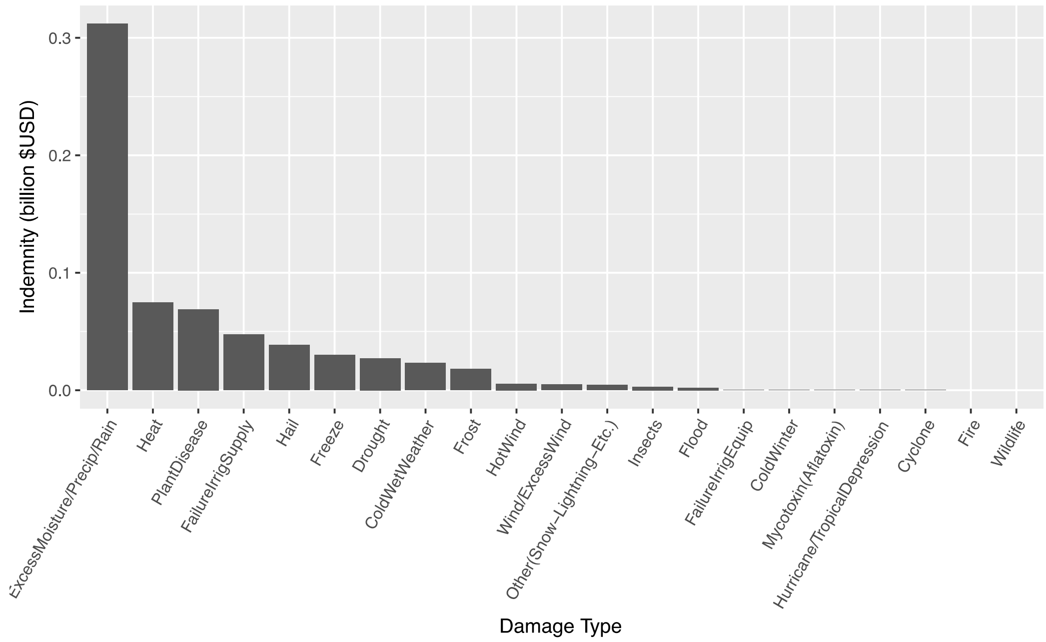


Figure 1. USDA RMA total indemnification value of potato losses by damage type, 2001–2016.

As mentioned, the Cause of Loss dataset also records the stage of the production process in which the crop was lost. The stages in which the majority of claims are made are "unharvested", "harvested", and "prevented planting". We explicitly do not count the prevented planting stage as it accounts for claims made in which famers were not able to begin the growing process. In such a case, they will not apply any water to these crops and thus is outside our scope of interest. Unfortunately, we must also largely exclude the harvested stage as well. These are claims in which the producer harvests the land but receives a lower yield than expected. While this is an important part of in-field losses, these calculations are based on detailed formulas that utilize proprietary information unique to each insured farm and public data is only available as dollar amounts or acres; thus, specifically estimating loss tonnage remains difficult for external researchers.

Another drawback of the RMA data source is that not every farmer takes out a crop insurance policy. In the largest producing states, anywhere from about 55%–98% of total potato acreage was insured in 2016 [34]. Thus, we expect any estimate of total losses derived from this data to be less than the NASS estimates. However, a feature of this data set is that all claims made to the agency are vetted by an auditor. Therefore, from this dataset we know at least this amount of crop was lost and in absolute terms can only use it as a baseline for comparison.

From the RMA data, we can compare the acreage of recorded losses with the total acreage insured to estimate the percentage of insured crop lost by damage type (Equation (2)).

$$RL_{s,d} = \frac{LR_{s,d}}{AR_s} \tag{2}$$

where,

$RL_{s,d}$ = Average relative agricultural potato losses based on RMA losses estimate by state (s) and damage type (d), 2012–2016

$LR_{s,d}$ = Average acreage of potato losses from the RMA data, 2012–2016, by state (s) and damage type (d)

AR_s = Average potato acreage harvested from RMA-insured farms, 2012–2016, by state (s)

We then extrapolate the percentage losses by state and damage type from the RMA data set to the total pre-harvest losses calculated from the NASS data to get average statewide pre-harvest losses by state by damage type $(IL_{s,d})$, 2012–2016, as shown in Equation (3).

$$IL_{s,d} = PL_s \times RL_{s,d} \tag{3}$$

where,

$IL_{s,d}$ = Imputed average acreage of potato losses by state (s) and damage type (d), 2012–2016

Like NASS, the RMA Cause of Loss data set also reports at the county level and single claim counties are omitted for privacy protections. The key difference between the NASS and RMA aggregations is that there is not a readily available state level Cause of Loss data set which incorporates the single claim counties. As a result, when we aggregate to the state level for the RMA data to compare to the NASS data, we are still missing the single claim counties.

2.2.3. NASS Objective Yield Survey

After assessing pre-harvest losses by acreage, we also wanted to explore losses that occur during the harvesting process. Since 2012, NASS has been collecting data on harvest potato losses via the OY survey [31]. For this measurement, NASS sends enumerators to fields immediately after harvest to measure how much crop is left in the ground after the mechanical harvesters pass through the field. These losses include the potatoes that are entirely missed by the harvester as well as the smaller potatoes that are sorted out by the harvester itself. The enumerators dig sample plots in harvested fields to collect and weigh the samples in order to calculate an estimate of production lost per acre. The enumerators limit their samples to being of $1\frac{1}{2}''$ in diameter and above to limit their assessment to include only what they consider to be marketable product [35]. We then take this estimate of production lost per acre and multiply by NASS's estimate of total acres harvested to receive an estimate of average harvest losses, 2012–2016 (Equation (4)).

$$HL_s = AH_s \times ML_s \tag{4}$$

where,

HL_s = Average total potato losses (tonnes) at harvest by state (s), 2012–2016

ML_s = Average measured losses (tonnes/acre) at harvest from the NASS OY survey by state (s), 2012–2016

As mentioned above, NASS only started collecting data on harvest losses in 2012. This is shorter than the period of available data for the pre-harvest losses (both NASS and RMA) and thus represents a limitation in the duration of time series data for harvest losses relative to pre-harvest losses. For the purpose of our study, we restrict the overall time period of analysis to 2012–2016 to harmonize our estimates across all of the in-field loss data sources.

Another limitation to the harvest loss data is that the OY survey only encompasses seven fall producing states in total: Idaho, Washington North Dakota, Minnesota, Oregon, Wisconsin, and Maine. Together these states account for the majority of total potato production in the U.S. (more than 77%) over our total sample period. It should also be noted that fall producing states (which include all the above-mentioned states) make up the majority of total U.S. potato production (more than 91%). Figure 2 summarizes production for the top 10 fall producing states for the period, 2012–2016. Idaho and Washington are the top two potato producing states, representing roughly 6.8 and 5.1 million metric tons (Mtonnes), respectively, of average potato production per year for 2012 to 2016 based on NASS estimates.

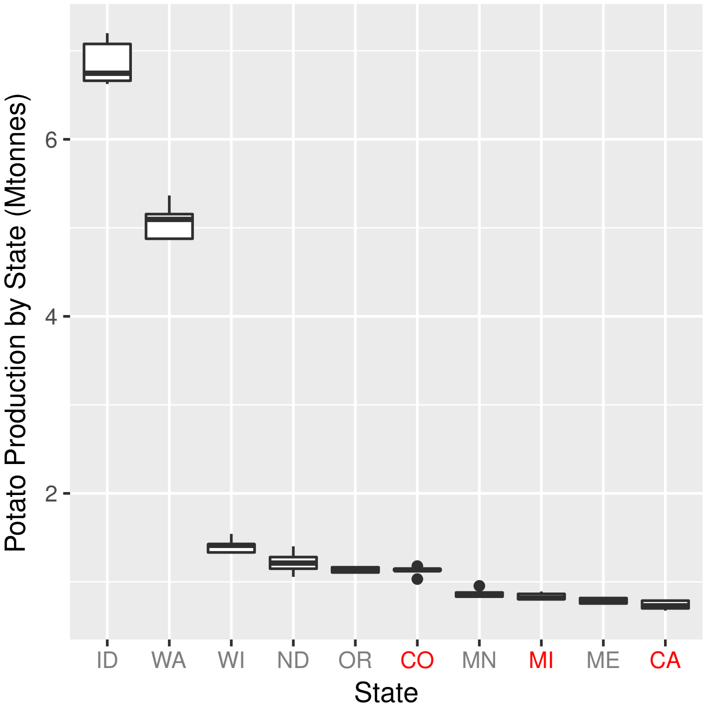


Figure 2. Boxplot of potato production for top 10 producing states, 2012–2016. States colored red are not in the OY survey. ID = Idaho, WA = Washington, WI = Wisconsin, CO = Colorado, ND = North Dakota, OR = Oregon, MN = Minnesota, ME = Maine, MI = Michigan, CA = California.

Although the survey includes a large portion of the total production, it may still be problematic to extend any averages derived from this survey to the national level. As mentioned, all the states involved in the OY survey are fall producing states. This is the most common season for potato production, however we may expect losses to be asymmetrical between spring and fall producing states due to different weather patterns, climactic conditions, and diseases. Thus, applying loss averages derived exclusively from fall producing states to spring producing states may be inaccurate. Therefore, in order to preserve the accuracy of our discussion, we limit our analysis to fall production in these seven states over this five-year time span.

2.2.4. Water Use Data: USDA NASS

To estimate the embedded water in the estimated potato losses, we leveraged the "water applied" data provided by the NASS FRIS. The FRIS occurs every five years in the year immediately following the census of agriculture [32]. Water use is estimated by the grower for the current year on an acre-foot/acre basis. For potatoes, data are only available from the 2013 FRIS, so the "water applied" estimate reflects water use estimates for 2013 cultivation. The water applied variable is reported for various irrigation technologies at the county and state levels. As with the NASS survey, there is potential for self-reporting bias in the survey design, but the centralized collection of this data does have the advantage of consistent data collection methodology from state to state.

Since NASS has only recorded the "water applied" variable for one year (2013), we cannot test the magnitude of change for water application conditional on precipitation, or if it changes at all. However, we did attempt to contextualize the water applied data for 2013 within the historical precipitation record by comparing 2013 precipitation data by month and state to the previous 50-year record. We found that 2013 precipitation exhibited some extreme conditions in both directions, where many states had months that were both abnormally wet and abnormally dry. Thus, there is no clear conclusion to be made on whether the water applied variable for 2013 is likely an over- or underestimation of water use compared to broader historical conditions. This counts as another shortcoming of available data for this area of study. Hopefully with more time and repeated measures, we can generate more robust assessments of the effect of precipitation on irrigation water application for potatoes and other crops tracked by NASS.

For our assessment, we used total water applied (regardless of technology type) by state. To harmonize the water use data to potato production units we converted the acre-foot/acre unit to m^3/tonne using the NASS-based yield values for irrigated acreage for 2012.

2.3. Estimating the Blue Water Footprint of Potato Losses

We utilize all the data sources described above to estimate the blue water footprint of potato losses for each reporting state in the NASS OY survey. We multiply each of the estimates of potato loss (IL_s and HL_s) by the NASS water applied data and the proportion of harvested acres that were irrigated in 2012 (Equations (5) and (6)). Note that this assumes that the overall proportion of irrigated acres does not vary over the sample period.

$$IW_s = IL_s \times WA_s \times \frac{IH_s}{AH_s} \tag{5}$$

$$HW_s = HL_s \times WA_s \times \frac{IH_s}{AH_s} \tag{6}$$

where,

IW_s = Average blue water footprint of pre-harvest potato losses (tonnes) by state (s), 2012–2016
WA_s = Water applied per tonne of potatoes produced on irrigated acres, 2012
IH_s = Irrigated acres harvested by state (s), 2012
HW_s = Average blue water footprint of harvest potato losses (tonnes) by state (s), 2012–2016

Adding these two estimates together produces an estimate of the total blue water footprint of potato losses by state (Equation (7)). To normalize these estimates, we divided the total blue water footprint of potato losses ($TW_s//0$ by the average total potential production (TP_s) by state (Equation (8)). This calculation creates a blue water footprint intensity metric (WI_s) that reflects the combined drivers of water use for crop losses by incorporating the effect of both the intensity of water applied to cultivate potatoes in each state as well as the losses per state relative to total potential production.

$$TW_s = IW_s + HW_s \tag{7}$$

$$WI_s = \frac{TW_s}{TP_s} \tag{8}$$

3. Results and Discussion

In the following section, we present and discuss the results of estimating blue water footprint for total in-field potato production loss, as well as disaggregated results at both the pre-harvest and harvest production phases. We review the blue water footprint calculations for the pre-harvest and harvest losses for each of the seven major potato producing states that have consistent data availability across the three major data sets used for the analysis. We also explore the implications of the relative efficiency of water use for potato cultivation by state in the context of both the intensity of irrigated water use as well as the embedded blue water footprint of in-field potato losses.

3.1. Comparison of Pre-Harvest Potato Loss Estimation: NASS and RMA

As discussed previously, we estimated the pre-harvest losses by damage type by extrapolating the percentage of total insured loss caused by each driver type from the RMA data to the estimate of total loss estimated by NASS. This procedure assumes that the loss driver cataloged by the RMA impacts those who are insured in the same way as those who are not.

To test this assumption, we plotted the proportional estimates of loss by dividing the estimates of absolute loss by the total amount produced (NASS) and acreage insured (RMA) respectively. We then constructed Figure 3 to plot these average relative losses for our seven selected states from 2001–2016. We chose to include years that were beyond the scope of our primary analysis to establish a long-run trend. The averages for relative losses are fairly consistent in their movement with a correlation coefficient of about 0.76. In this unitless measure, the average proportional loss values overall are about 2.2% for NASS and 0.8% for RMA. For comparison, this is right in line with the 1–2% estimate of in-field losses from a study focused on potato cultivation and losses in the UK [36]. Based on these results, we feel that we can reasonably apply the proportion of losses due to each driver in the RMA data set to the total pre-harvest losses derived from the NASS survey data. By doing so, we can evaluate approximately how much of the pre-harvest losses are being caused by each driver.

It should be noted that there are some observations in which NASS records significant in-field losses for a state while RMA receives very little insurance claims for the pre-harvest stage for that same state. In these cases, we used the proportional damage types from the "harvested" stage of the RMA data. Our decision rule for this method was if the ratio of RMA unharvested claims to the NASS data was smaller than 5% we would use the damage types from the harvest stage. Our justification for this is that drivers of loss are typically factors (weather, disease, insects, etc.) that would likely affect many farms in a region and would be persistent problems. In sum, we are assuming that the decision of a farmer to not harvest a field is most likely caused by the same external driver that is leading to decreases in yield at other farms in the region. While this not an ideal extrapolation of the driver data, we feel it is a sufficient approximation.

3.2. Pre-Harvest and Harvest Potato Losses

The results of our pre-harvest potato loss estimates that combine both NASS and RMA data are provided in Figure 4. For ease of visualization, we clustered the RMA driver categories as follows: Precipitation/Flood (rain, cold wet weather, hail, and flood); Drought/Heat/Wind (drought, heat, hot wind, and excess wind); Freeze/Frost; Insect/Disease, and Other. Figure 4A shows the relative percentage of losses by driver type for each state. The vast majority of losses are driven by the precipitation/flood category. Drought, heat, and wind generate sizable losses in Idaho, Wisconsin, North Dakota, Oregon, and Minnesota, while insects and disease play a significant role in generating pre-harvest losses in Idaho, Wisconsin, Oregon, and Maine. Oregon and Idaho have the largest proportion of losses caused by freeze and frost, with some impact occurring in Wisconsin as well.

Meanwhile Figure 4B shows the absolute quantities of both pre-harvest and harvest losses for each of the seven states. While Idaho, Washington, and Wisconsin are the top producers (Figure 2), North Dakota shows by far the highest pre-harvest losses—more than 4-fold higher than each of the three leading producers. While the data tell us the vast majority of these losses are from precipitation/flood drivers, it is not immediately apparent why the total amount of losses are so much higher than the other states. Perhaps this is an area for future inquiry for this particular state.

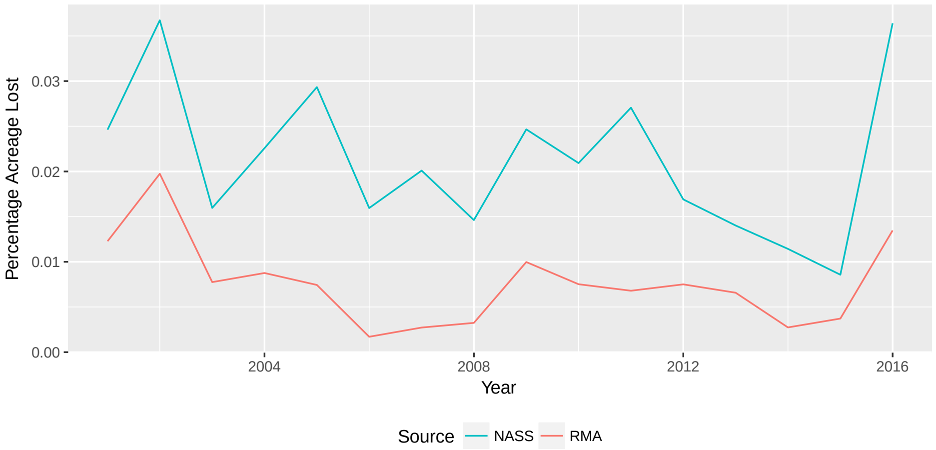


Figure 3. Relative agricultural production potato loss acreage estimated from USDA NASS and RMA data sources for selected seven states, 2001–2016.

Figure 4B also shows that harvest losses are significantly greater than pre-harvest losses in every state. The two largest producers (Idaho and Washington) show the highest levels of harvest losses (approximately 380,000 and 168,000 tonnes, respectively), which makes sense as the total amount of losses should scale with production. However, North Dakota once again shows outsize losses (147,000 tonnes) for its ranking in total production by state. The complete data set for Figure 4 is provided in Appendix A (Table A1).

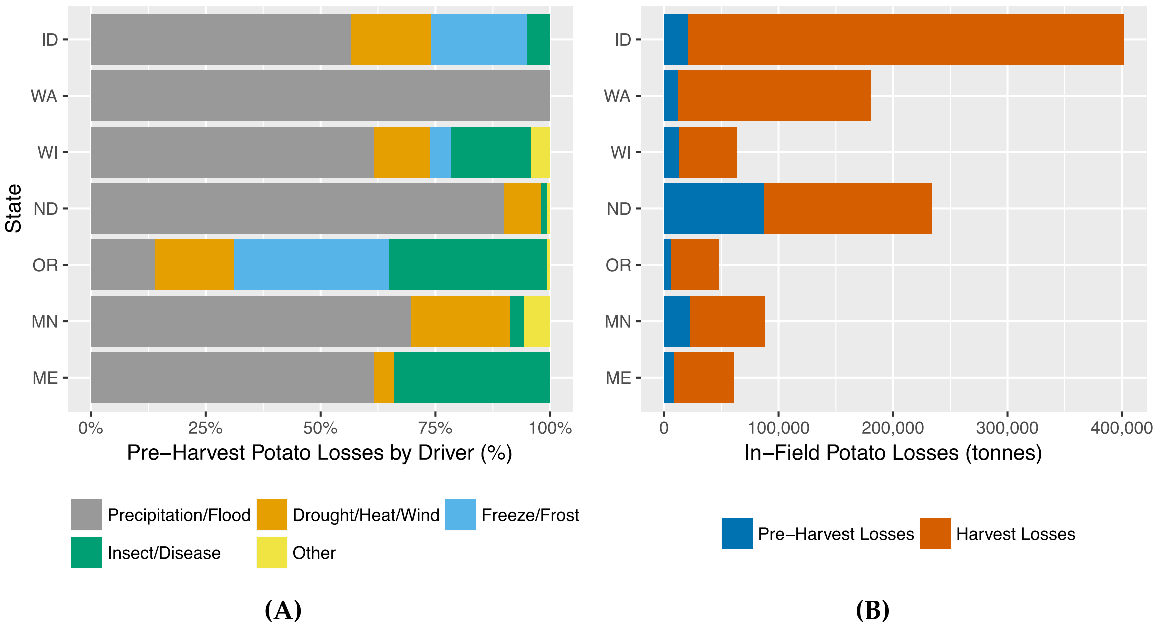


Figure 4. Average percentage of annual pre-harvest losses by driver of loss and state, 2012–2016 (**A**) and average annual pre-harvest and harvest losses in tonnes by state, 2012–2016 (**B**).

Average pre-harvest losses and harvest losses are presented relative to total production in Figure 5. The percentage losses for both harvest and pre-harvest losses are identified on the graphic, respectively. As discussed previously, North Dakota shows the greatest percentage pre-harvest losses (6.7%), followed by Minnesota (2.5%), Maine (1.1%), and Wisconsin (0.9%). North Dakota also demonstrates the greatest relative harvest losses (11.2%), followed by Minnesota (7.4%), Maine (6.6%), and Idaho (5.5%). Another way to consider this graphic is that the full bar for each state represents the total *potential* potato production, while the gray portion of the bar represents *actual* potato production after accounting for total in-field losses (both pre-harvest and harvest losses). The complete data set for Figure 5 is provided in Appendix A (Table A2).

It is worth noting that the drivers of loss at the pre-harvest stage are all environmental factors that are largely out of the control of the grower. While some steps can be taken to mitigate damage to crops (e.g., planting windbreaks around the perimeter of a plot) these factors will likely remain largely unavoidable in the cultivation of potatoes [37]. That said, given the spatial heterogeneity of the observed losses, it is clear that some locations are better suited for potato cultivation than others from a loss perspective. Of course, the actual decision to cultivate is based more on market factors (including access to insurance), which is a discussion beyond the scope of this paper.

While the pre-harvest losses are more dependent on a range of drivers, the driver of loss at the harvest stage depends on the efficiency and calibration of the mechanized harvester. Most of the gains that can be made in this phase of production are technical improvements to machinery and fall on harvester manufacturers. However, farmers could potentially improve their harvest efficiency by purchasing new sorting chains with smaller spacing in order to collect smaller product, hiring extra staff to monitor harvester efficiency during the harvesting process, and upgrading to more modern equipment [37].

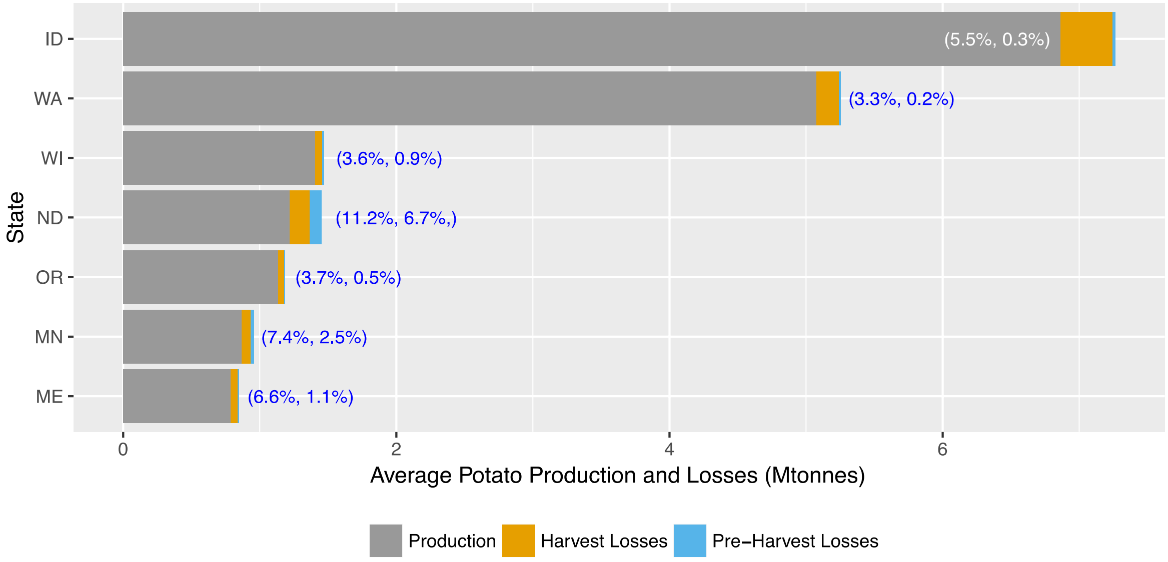
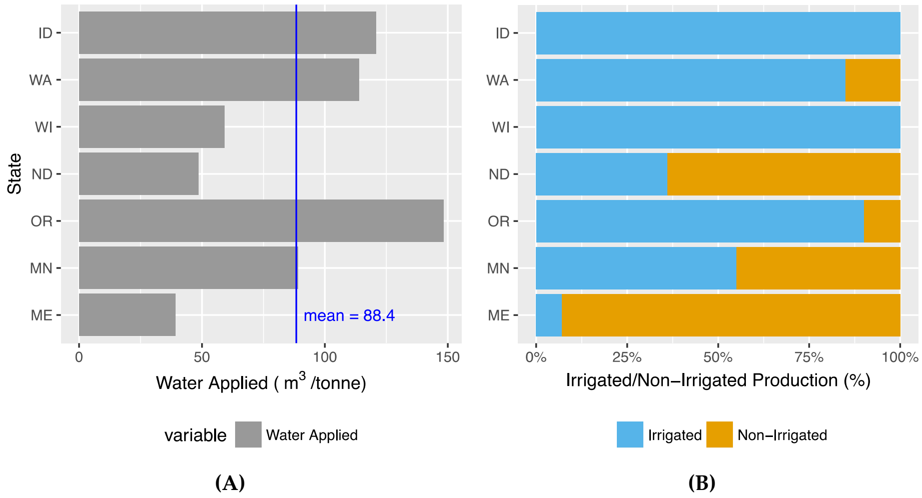


Figure 5. Average annual pre-harvest and harvest losses relative to total potential production, 2012–2016.

3.3. Blue Water Footprint Results

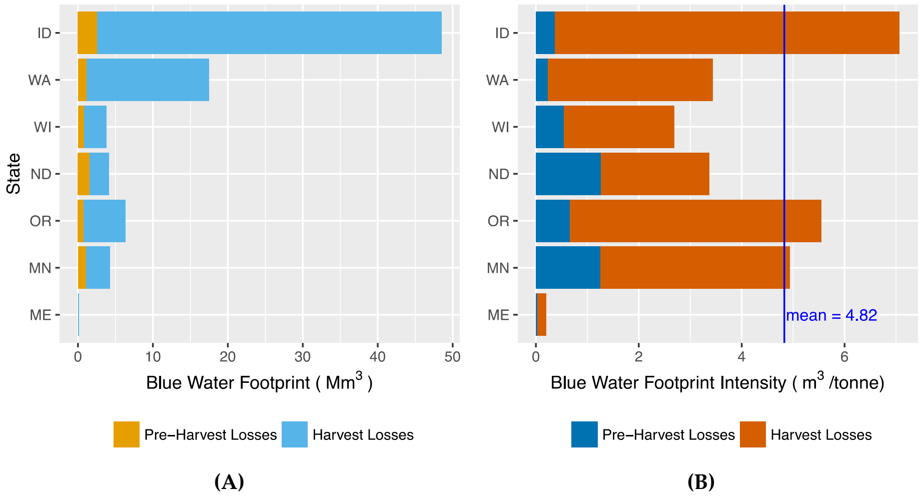
We estimated the total blue water footprint for pre-harvest and harvest potato losses for the seven states with OY survey data. Figure 6 summarizes the NASS "water applied" data for 2013 for irrigated acreage in each state (A) as well as proportion of irrigated to non-irrigated acreage (B). The average state value for water applied is 88.4 cubic meters (m^3) per tonne of potatoes produced under irrigation. Oregon shows the highest amount of water applied (148 m^3/tonne), followed by Idaho, Washington, and Minnesota (121, 114, and 89 m^3/tonne, respectively). Meanwhile, there is great variation in the proportion of acreage under irrigated cultivation from state to state, ranging from Idaho and Wisconsin showing 100% irrigated acreage to Maine with roughly 7% irrigated acreage. The percent of irrigated acreage has a heavy influence on the total blue water footprint, which only includes irrigated water use and agriculture cultivated under a rain-fed regime.



(A) **(B)**

Figure 6. Water applied (2012) data from 2013 NASS FRIS (**A**). Average annual proportion of irrigated to non-irrigated acreage, 2012–2016 (**B**).

Multiplying water applied and percentage of irrigated potato cultivation by the loss results yields the blue water footprint of pre-harvest and harvest potato losses (Figure 7A). Idaho has by far the greatest total amount of embedded water in its in-field potato losses at 48.5 million cubic meters (Mm^3). This is not too surprising given the large-scale of Idaho's potato production, the heavy reliance on irrigation for potato cultivation relative to other states, and the above average application of water per tonne of potato produced. However, Washington shows a much lower overall blue water footprint of in-field losses (17.5 Mm^3) despite its own high production reliance on irrigation. Meanwhile, the blue water footprint in potato losses in Oregon (6.3 Mm^3) is noticeably high relative to the other lower volume production states.



(A) **(B)**

Figure 7. Average annual blue water footprint (**A**) and blue water footprint intensity (**B**) for average in-field potato losses by state, 2012–2016.

For a more direct comparison of the in-field potato loss blue water footprint relative to total production, we directly normalized the water footprint estimations by production by state (Figure 7B). This normalization provides an estimate of the intensity of the water footprint of potato losses in relative terms, rather than in absolute quantities. Consistent with the previous results, Idaho and Oregon stand out as having a particularly intensive water footprint of in-field potato losses at 7.07 m^3 and 5.55 m^3 of water embedded in each tonne of potato losses, respectively. These states are the only two states that exceed the value of the weighted average of the water footprint intensity across all states in the study (4.82 m^3/tonne). Minnesota has the next highest water footprint intensity (4.94 m^3/tonne) that falls just above the weighted average across states. The remaining states are mostly within the same range (2.69 to 3.45 m^3/tonne), with the notable exception of Maine that demonstrates by far the lowest level of embedded irrigation water in its in-field potato losses at 0.21 m^3/tonne, a result of its very low utilization of irrigation for potato production (only 7% of acreage is irrigated, as shown previously). The complete data set for Figures 6 and 7 is provided in Appendix A (Table A3).

4. Conclusions

As described in the previous section, there is no single data source that provides a clear estimate of in-field crop losses in the United States, so multiple data sources needed to be leveraged and integrated for this study. The USDA NASS survey data provides excellent coverage of farm production data with data for every county since the beginning of the 20th century. While the NASS survey for potatoes enables estimation of pre-harvest losses by providing estimates of both acres planted and acres harvested, these variables are not collected consistently across all crops types, which currently limits broader analysis of in-field crop types. The USDA RMA data provides additional dimension to pre-harvest losses by identifying drivers of the crop losses, but these data are only available more recently (since 2001) and only represent insured (and claimed) losses in the U.S. and not total losses. USDA NASS OY survey data provide estimates of losses at harvest, but is limited to the last five years, only to potatoes in the vegetable category, and only for the seven selected fall-producing states. Finally, the NASS FRIS data provides an estimate of water applied for potatoes, but the survey is only collected every five years and there is only one year available so far (and once again, only for potatoes in the vegetable category).

Despite the limitations of each of these data sources, in combination they present sufficient information for a high-level assessment of the embedded water associated with the in-field losses of potato production in seven major states in the United States. We found that 84.6 Mm^3 of water is associated with in-field potato losses in the seven states of our study: Idaho, Washington, Wisconsin, North Dakota, Oregon, Minnesota, and Maine. The highest total blue water footprint (48.5 Mm^3) and intensity of water use embedded in losses relative to total potato production was observed in Idaho (7.07 m^3/tonne), which was largely driven by the large amount of both pre-harvest and harvest losses for potatoes as well as its heavy reliance on irrigated potato cultivation. Harvest losses were consistently higher than pre-harvest losses in all states, so efforts to reduce losses have the most potential for absolute reduction by targeting this category. Further, reduction in harvest losses might be more achievable since weather-based pre-harvest losses may be harder to mitigate, and there does seem to be some potential to direct smaller potatoes that are currently sorted out into the marketplace.

The broad range of blue water footprint intensities for in-field potato losses from state to state suggests that some states have a disproportionate amount of water embedded in their losses and perhaps could strive to be more efficient or pursue other crops. As discussed before, there may be limited opportunity to reduce pre-harvest losses driven by weather that is largely outside the control of the grower. For harvest losses, perhaps the acceptance of smaller potatoes by the market could lead to significantly lower quantities of harvest losses. In an anecdotal discussion with an Extension Specialist at Michigan State University, we learned that smaller potatoes may even be more desirable for snack-size potato chip bags where lower breakage has been observed for that particular packaging [37]. Additional opportunities may exist in secondary markets, where smaller or misshapen potatoes may be sold as "ugly" or "imperfect" produce at a discount to the consumer, or sold to processors where shape and size do not matter, such as the expanding production of potato protein isolate within the plant-based protein market [38].

The final lever for reducing the embedded water in the potato losses is to reduce the amount of water applied in irrigated potato cultivation, but evaluating alternative irrigation technologies and strategies for potato cultivation is beyond the scope of this paper.

Data collection in this area of study has been improving over time, and without recent additions to USDA surveys we would not have been able to complete this paper. That said, there are still many improvements to be made. We were only able to complete this analysis for potatoes as it was the only crop that had all of the necessary data readily available. Further, many of the data points used in this paper were only recently collected. This leaves any analysis of trends and causal relationships difficult or impossible to complete. For instance, the FRIS was only conducted for potatoes in 2013 as a supplement for the Census of Agriculture. As a result, no analysis could be performed on important topics such as: how weather patterns affect water application or how irrigation practices changing over time. We applaud the expansions in data collection that have been made, and hope that more robust and sustained data gathering will continue to enable further analysis by crop type and over time.

As momentum continues to build around the economic and environmental consequences of food loss and waste within both the research community and with policymakers, the improved availability and quality of data on the flows of loss and waste through the supply chain will become more and more important. Given the unique availability of data on this topic specifically relevant to potatoes, perhaps this crop can serve as the model to enhance and harmonize USDA farm-level data collection efforts on additional crops and regions moving forward. This would enable similar studies of not just embedded water, but other critical economic and natural resource investments in agriculture that are lost with forfeited crop production. Further, the importance of understanding these linkages and impacts has only increased in the dynamic context of climate change that may shift the weather-based drivers of loss over time, as well as the availability and reliability of regional resources, including water supplies.

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Appendix A

Table A1. Pre-Harvest Losses by Damage Type and Harvest Losses, 2012–2016 (tonnes).

Loss Category	Idaho	Washington	Wisconsin	North Dakota	Oregon	Minnesota	Maine
Excess Rain	9600	9163	8094	71,849	575	13,047	5564
Cold Wet Weather	387	3131	0	3101	185	0	0
Hail	1640	0	0	3094	37	0	27
Flood	348	0	0	439	0	2628	0
Precipitation/Flood	*11,975*	*12,294*	*8094*	*78,482*	*796*	*15,675*	*5590*
Drought	0	0	0	6223	0	4858	381
Heat	3039	0	1575	669	966	0	12
Hot Wind	242	0	0	0	0	0	0
Excess Wind	383	0	0	0	0	0	0
Drought/Heat/Wind	*3665*	*0*	*1575*	*6892*	*966*	*4858*	*393*
Freeze	1373	0	0	0	1676	0	0
Frost	3020	0	619	0	234	0	0
Freeze/Frost	*4393*	*0*	*619*	*0*	*1910*	*0*	*0*
Insect	0	0	0	0	13	0	504
Disease	1071	0	2261	1290	1922	688	2581
Insect/Disease	*1071*	*0*	*2261*	*1290*	*1936*	*688*	*3085*
Other	*0*	*0*	*559*	*513*	*41*	*1284*	*0*
Pre-Harvest Losses	21,103	12,294	13,107	87,177	5649	22,505	9068
Harvest Losses	380,387	168,298	50,751	146,788	41,816	65,667	52,159
Total Losses	**401,491**	**180,592**	**63,858**	**233,965**	**47,466**	**88,172**	**61,227**

Table A2. Average Potential Potato Production Relative to Losses, 2012–2016.

Production/Loss Category	Idaho	Washington	Wisconsin	North Dakota	Oregon	Minnesota	Maine
Potential Production (tonnes)	6,883,458	5,085,819	1,420,432	1,307,346	1,141,731	891,174	795,818
Pre-Harvest Losses (tonnes)	21,103	12,294	13,107	87,177	5649	22,505	9068
Harvest Losses (tonnes)	38,0387	168,298	50,751	146,788	41,816	65,667	52,159
Total Losses (tonnes)	*401,491*	*180,592*	*63,858*	*233,965*	*47,466*	*88,172*	*61,227*
Pre-Harvest Losses (%)	0.3%	0.2%	0.9%	6.7%	0.5%	2.5%	1.1%
Harvest Losses (%)	5.5%	3.3%	3.6%	11.2%	3.7%	7.4%	6.6%
Total Losses (%)	*5.8%*	*3.5%*	*4.5%*	*17.9%*	*4.2%*	*9.9%*	*7.7%*

Table A3. Water applied and percent irrigated acreage (2013) and average blue water footprint and blue water footprint intensity (2012–2016).

Indicator	Idaho	Washington	Wisconsin	North Dakota	Oregon	Minnesota	Maine
Irrigated Water Applied (m^3/tonne)	121	114	59	49	148	89	39
Percent Irrigated Acreage (%)	100%	85%	100%	36%	90%	55%	7%
Blue Water Footprint (Mm3)	48.50	17.49	3.78	4.11	6.31	4.29	0.16
Pre-Harvest	*2.55*	*1.19*	*0.78*	*1.53*	*0.75*	*1.09*	*0.02*
Harvest	*45.95*	*16.30*	*3.01*	*2.58*	*5.56*	*3.19*	*0.14*
Blue Water Footprint Intensity (m^3/tonne)	7.07	3.45	2.69	3.37	5.28	4.94	0.21
Pre-Harvest	*0.37*	*0.23*	*0.55*	*1.26*	*0.63*	*1.26*	*0.03*
Harvest	*6.70*	*3.21*	*2.14*	*2.11*	*4.65*	*3.68*	*0.17*

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