agronomy

Article

Potato Growth and Yield Characteristics under Different Cropping System Management Strategies in Northeastern U.S. †

Robert P. Larkin [1,*], C. Wayne Honeycutt [2], Timothy S. Griffin [3], O. Modesto Olanya [4] and Zhongqi He [5]

[1] USDA-ARS, New England Plant, Soil, and Water Laboratory, University of Maine, Orono, ME 04469, USA
[2] Soil Health Institute, Morrisville, NC 27560, USA; whoneycutt@soilhealthinstitute.org
[3] Friedman School of Nutrition Science and Policy, Tufts University, Boston, MA 02111, USA; Timothy.Griffin@tufts.edu
[4] USDA-ARS, Eastern Regional Research Center, Wyndmoor, PA 19038, USA; modesto.olanya@usda.gov
[5] USDA-ARS, Southern Regional Research Center, New Orleans, LA 70124, USA; zhongqi.he@usda.gov
* Correspondence: bob.larkin@usda.gov; Tel.: +1-207-581-3367

† Mention of trade names, proprietary products, or specific equipment does not constitute a guarantee or warranty by the U.S. Department of Agriculture and does not imply approval to the exclusion of other products that may be suitable.

Abstract: Cropping systems and management practices that improve soil health may greatly enhance crop productivity. Four different potato cropping systems designed to address specific management goals of soil conservation (SC), soil improvement (SI), disease suppression (DS), and a status quo (SQ) standard rotation, along with a non-rotation (PP) control, were evaluated for their effects on potato crop growth, nutrient, and yield characteristics under both irrigated and non-irrigated (rainfed) conditions in field trials in Maine, USA, from 2004 to 2010. Both cropping system and irrigation significantly ($p < 0.05$) affected most potato crop parameters associated with growth and yield. All rotations increased tuber yield relative to the non-rotation PP control, and the SI system, which included yearly compost amendments, resulted in overall higher yields and a higher percentage of large-size tubers than all other systems with no irrigation (increases of 14 to 90%). DS, which contained disease-suppressive green manures and cover crops, produced the highest yields overall under irrigation (increases of 11 to 35%). Irrigation increased tuber yields in all cropping systems except SI (average increase of 27–37%). SI also resulted in significant increases in leaf area duration and chlorophyll content (as indicators of photosynthetic potential) and root and shoot biomass relative to other cropping systems, particularly under non-irrigated conditions. SI also resulted in higher shoot and tuber tissue concentrations of N, P, and K, but not most micronutrients. Overall, cropping systems that incorporate management practices such as increased rotation length and the use of cover crops, green manures, reduced tillage, and particularly, organic amendments, can substantially improve potato crop growth and yield. Irrigation also substantially increased growth and yield under normal field conditions in Maine, but SI, with its large organic amendments, was essentially a substitute for irrigation, producing comparable results without irrigation.

Keywords: compost amendment; cover crops; crop production; green manure; leaf area duration; soil health; tuber yield

Citation: Larkin, R.P.; Honeycutt, C.W.; Griffin, T.S.; Olanya, O.M.; He, Z. Potato Growth and Yield Characteristics under Different Cropping System Management Strategies in Northeastern U.S. *Agronomy* **2021**, *11*, 165. https://doi.org/10.3390/agronomy11010165

Received: 17 December 2020
Accepted: 13 January 2021
Published: 16 January 2021

1. Introduction

Sustainability of crop production systems is dependent on many factors, from the cost/benefit of the many operations involved to the inputs and outputs obtained to the continued health of the soil and overall agroecosystem. Probably the most important single attribute to growers is crop productivity, usually measured by yield. Crop yield is the final result, but numerous aspects of crop development and growth may be involved in or responsible for the resultant yield observed, and may give indications of where production problems may be occurring. Soil health, defined as the continued capacity of soil to function as a vital living system to sustain biological productivity; maintain environmental quality; and promote plant, animal, and human health [1–3] is a critical component of agricultural productivity, sustainability, and ecosystem function. Incorporation of soil and crop management practices that promote soil health, such as crop rotations, cover crops and green manures, organic amendments, and conservation tillage, into improved cropping systems may help maintain and/or improve soil health and enhance productivity, sustainability, economic vitality, and environmental quality [3,4].

Potato (*Solanum tuberosum* L.), an important crop in the US and throughout the world, can be particularly hard on soils due to the intensive tillage operations and cropping patterns used. Potato production in the northeast U.S., as well as in other potato growing regions, has been characterized by short (2 y) rotations, extensive tillage, minimal crop residue return, and minimal crop diversity, often taking a toll on soil health and crop productivity over time [5]. Increasing rotation length from 2 years to 3 or more years between potato crops has been shown to improve productivity, as well as reduce soilborne diseases in multiple studies [6–10]. Other practices, such as the addition of cover crops and green manures [11,12], amendments of compost or animal manure [13–15], and reduced tillage [6,16], have all shown promise for having positive effects on tuber yield and quality, as well as other benefits to various soil properties and soil health in potato systems. However, most previous research has focused on the assessment of individual practices or rotations, and not necessarily on the combined effects of multiple different practices in integrated cropping systems for the total system effects on productivity and plant and soil properties.

In this research, which builds upon our previous work with improving potato cropping systems [17–21], we assessed the effects of cropping systems incorporating multiple soil health management practices focused on specific soil and crop management goals, on various plant characteristics of the potato crop itself, including growth, productivity, and nutrient concentrations. In 2004, we established field trials for long-term evaluation of different potato cropping systems to better determine what factors were most limiting to potato production in Northeastern U.S., and how these limitations could be addressed through cropping systems [20]. Three specific cropping systems were established to address the crop and soil management goals of soil conservation, soil improvement, and disease suppression, and these were compared to a standard rotation and a non-rotation control.

Previously, we characterized the effects of these cropping systems on various management concerns, such as soilborne potato diseases and soil microbiology [20–23], soil health (represented by various soil physical, chemical, and biological properties) [24,25], and soil nutrient-related enzyme activities and P status [26–28]. In the present research, we examined cropping system effects on crop productivity using such crop characteristics as photosynthetic potential (measured as leaf area index and chlorophyll content), tuber yield and quality (total and various size class distributions, misshapenness, and specific gravity), biomass production (both above- and below-ground), and plant tissue nutrient concentrations.

2. Materials and Methods

2.1. Cropping Systems

Cropping systems consisted of five different systems designed to address specific management goals of soil conservation, soil improvement, and disease suppression, as well as a system representing a typical standard rotation currently used in the Northeast U.S., and a non-rotation control of continuous potato. An overview of the cropping systems and their features is provided in Table 1, which have been previously described [20]. In brief, the standard or "status quo" (SQ) rotation consisted of a 2 y rotation of barley (*Hordeum vulgare* L.) underseeded with red clover (*Trifolium pretense* L.) as a cover crop, followed by potato the following year, and includes regular spring and fall tillage each year. The soil conserving (SC) system consisted of a 3 y rotation of barley underseeded with the forage grass timothy (*Phleum pratense* L), which would overwinter and be allowed to continue undisturbed for a full year (2nd y), and then followed by potato in the third year. In this system, tillage was also greatly reduced, with no tillage except as needed for maintenance and harvest in the potato crop year, thus substantially improving soil conservation. In addition, straw mulch (2 Mg/ha) was applied after potato harvest to further conserve soil resources. The soil improving (SI) system consisted of the same basic rotation as SC (3 y, barley/timothy-timothy-potato, limited tillage, straw mulch), but with yearly additions of compost (composted dairy manure added at 45 Mg/ha fresh wt [~18 Mg/ha dry wt]), to provide abundant organic matter to improve soil quality. The disease-suppressive (DS) system was designed to make use of multiple strategies for suppressing soilborne diseases, and included the use of disease-suppressive rotation crops, a longer rotation period, crop diversity, green manures, and fall cover crops. The DS system consisted of a 3 y rotation with the disease-suppressive *Brassica* "Caliente 119" Mustard Blend (blend of oriental and white mustard seeds, *Brassica juncea* L. and *Sinapis alba* L.) grown as a green manure, followed by a fall cover crop of rapeseed (*Brassica napus* L."Dwarf Essex") in the first year. In the second year, a disease-suppressive Sorghum–Sudangrass hybrid (*Sorghum bicolor* x *S. bicolor* var. *sudanense* L.) was grown as a green manure, followed by a fall cover crop of winter rye (*Secale cereale* L.), with potato in the third year. For this study, green manure refers to a crop whose full biomass was incorporated into the soil while fresh and green, whereas cover crop refers to a crop that is left in the field to overwinter unplowed and uncut. Continuous potato (PP) was the non-rotation control consisting of a potato crop planted in the same plots each year (spring and fall tillage). All cropping systems were evaluated under both irrigated and non-irrigated management. Irrigation was applied with a lateral, overhead sprinkler system when soil tensiometer readings at the 10–15 cm depth exceeded 50 KPa. Each irrigation event consisted of application of 1.3 cm of water.

Table 1. Names, descriptions, and features of the cropping systems used to address specific management goals in these studies.

Cropping System Parameters				
Name	**Abbreviation**	**Length**	**Rotation Description**	**Features**
Status Quo	SQ	2 y	Barley/Clover, Potato	Typical rotation (Industry standard)
Soil Conserving	SC	3 y	Barley/Timothy, Timothy, Potato	Additional year of forage, limited tillage, straw mulch after potato
Soil Improving	SI	3 y	Barley/Timothy, Timothy, Potato	SC plus yearly compost amendments
Disease-Suppressive	DS	3 y	Mustard GM/Rapeseed cover, Sudangrass GM/Rye cover, Potato	Biofumigation crops, green manures, cover crops, and increased crop diversity
Continuous Potato	PP	1 y	Potato, Potato	Non-rotation control

2.2. Field Set-Up and Management

Long-term research plots were established in 2004 at the USDA-ARS New England Plant, Soil and Water Laboratory Field Experimental Site in Presque Isle, Maine, USA, as a split-block design with 5 replicate blocks, with irrigation (Irr) and cropping system (CS) as the main and split factors, respectively. Soil type was a Caribou sandy loam (Fine-loamy, isotic, frigid Typic Haplorthods). Each rotation entry point (representing each possible rotation crop for all years) was included in each block, so that each full rotation was represented each year (SQ, 2 entry points; SC, SI, and DS, 3 entry points; and PP, 1 entry point), resulting in 12 treatment plots (6 $\times$ 15 m each) per block for each of the irrigated and non-irrigated components. Average soil properties measured at the time of initial planting (with no significant differences among treatment plots) were as follows: pH 5.88, total soil C 22.5 g kg^{-1} soil, soil N 1.7 g kg^{-1}, P 17.7 mg kg^{-1}, K 139 mg kg^{-1}, Ca 607 mg kg^{-1}, Mg 158 mg kg^{-1}, and CEC 5.58. For potato planting, seed tubers of the potato variety "Russet Burbank" were cut to seedpieces of ~50–60 g each 7 to 10 days prior to planting and stored at 8 °C until 48 h prior to planting, when they were stored at room temperature until planted. Seedpieces were planted by hand in furrows in each plot (four rows, 0.9 m centers, with a 35 cm spacing between plants). Potato plots were fertilized with the equivalent of 224 kg ha^{-1} N and 249 kg ha^{-1} P_2O_5 and K_2O. Fertilizer rate was based on years of previous research for this region in similar soils establishing 150–200 kg N ha^{-1} as optimal for potato production [29–33]. Fertilizer applications were purposely applied to be equal across all systems and above optimal rates for crop nutritional needs, so that nutrition would not be limiting in any cropping system and observed system effects would likely be related to factors other than fertility. Further details of the planting and management of the crops and rotations have been described previously [20].

Site environmental conditions, including air and soil temperature, relative humidity, and rainfall were monitored throughout each growing season using a CR10X datalogger (Campbell Scientific Inc., Logan, UT, USA) outfitted with temperature probes and a tipping bucket rain gauge. Data were recorded every hour and converted to daily minimum, maximum, and average values as well as total daily rainfall. For ease of presentation, temperature and rainfall data were summarized as average monthly values, and are presented along with the number of individual irrigation events for each year of the study (Table 2).

Table 2. Average daily temperature, total rainfall, and number of irrigation events for the months of May through September at the Presque Isle research site for 2006 to 2010 compared with long-term (30 year) average conditions.

	Environmental Parameters					
	2006	**2007**	**2008**	**2009**	**2010**	**Long-Term Avg**
Average Daily Temperature (°C)						
May	12.7	10.7	10.3	11.3	13.1	11.4
June	18.1	16.7	15.9	14.7	16.2	16.4
July	20.3	19.0	20.4	13.4	20.8	19.0
August	16.1	17.3	17.7	15.9	18.8	18.2
September	13.1	14.1	13.6	11.7	14.6	13.2
Season avg	16.1	15.6	15.6	13.4	16.7	15.6
Rainfall (cm)						
May	11.3	6.1	5.3	12.5	6.5	8.7
June	10.9	5.1	11.6	8.6	13.0	8.6
July	11.7	9.8	8.2	12.2	7.2	9.4
August	6.3	12.0	11.2	5.9	3.3	10.0
September	7.1	4.3	7.9	3.8	7.2	8.7
Season total	47.3	37.3	44.2	43.0	37.2	45.4
Irrigation events (no.)	3	6	4	0	6	

2.3. *Tuber Yield and Quality Assays*

In October of each year, potatoes were harvested from the full-length of the center two rows from each potato plot. Total weight of the harvested tubers was used to determine total yield on a Mg/ha basis. A subset of the harvested tubers, amounting to a total of 20–25 kg/plot and taken from multiple randomly selected plot sections, were washed, graded, and sized into 4 categories from small to extra large (small, <114 g; medium, 114–227 g; large, 228–342 g; and extra large >342 g). Marketable yield was calculated as the total weight of tubers of a size greater than 114g each. Tuber specific gravity was assessed on the graded subset of marketable tubers for each plot using standard weight in air vs. weight in water calculations. The weight of severely misshaped tubers (due to knobs, irregular shapes) from all size classes was also assessed for each plot.

2.4. *Crop Growth Assays*

2.4.1. Leaf Area Index, Duration, and Chlorophyll Content

Potato canopy density and light interception were estimated by the leaf area index (LAI), which is a measure of leaf area per unit of ground area, and leaf area duration (LAD), which is a measure of LAI over time. LAI was measured using the SunScan Canopy Analysis System (Dynamax Inc., Houston, TX, USA) which assesses the photosynthetically active radiation above and below the canopy and calculates LAI. Starting around 60 days after planting (DAP) and continuing once each week for 9–10 weeks thereafter, LAI was estimated in each plot, with a minimum of 12 below canopy readings made/plot at each sampling. LAD was determined from plots of LAI over time as the area under the LAI progress curve, and calculated as the integration of 2nd order polynomial functions generated through linear regression of LAI versus time (in DAP).

Leaf chlorophyll content was measured at the same time and same weekly schedule as LAI readings using the Minolta SPAD-502 chlorophyll meter (Spectrum Technologies, Plainfield, IL, USA). For each plot, 12 leaflets were sampled (third terminal leaflet from top of plant) from random plants at each sampling date. SPAD values indicated relative chlorophyll content, and were analyzed for individual sampling dates, as well as averaged over all sampling dates to give an overall season average for comparison among cropping systems.

2.4.2. Root, Tuber, and Shoot Biomass

Potato plant samples for biomass determinations were collected in mid-August (80–85 DAP) in the years 2007, 2008, and 2009. Four whole potato plants (2 each from the 2 center rows), including full root systems and developing tubers, were randomly selected in each plot, and removed intact from the soil. Plants were separated into root, tuber, and shoot components and weighed fresh, and then brought back to the lab. Roots and tubers were washed (to remove soil and adhering debris), and all plant parts were oven-dried (65 °C for 1 week in a drying oven) and weighed again. Dry weights per plot were then converted to biomass on an area basis (Mg/ha).

2.4.3. Root, Tuber, and Shoot Tissue Composition

In 2008 only, subsamples from plant samples collected for biomass determination were also analyzed for full elemental composition to compare nutritional qualities of the plant material among treatments. Subsamples were dried and ground in a Wiley mill (1-mm screen). Plant tissue C and N were determined by dry combustion using an elemental analyzer. Plant tissue concentrations of Ca, K, Mg, P, Al, B, Fe, Mn, Zn, and Cu were analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES) by the University of Maine Analytical Lab (Orono, ME, USA). Values were expressed as mg kg^{-1} dry weight of tissue.

2.5. Statistical Analyses

Data were analyzed using standard analysis of variance (ANOVA) with factorial treatment structure and interactions appropriate for a split-block design. Data from each crop year were analyzed separately, and then data from multiple seasons were also combined and analyzed (with year as additional factor, with interactions) together to evaluate cumulative and multi-year effects of the cropping systems. Correlation analyses were conducted (using Pearson's product-moment correlation coefficients) among crop growth, yield, and other soil property parameters (from soil properties determined as part of a previously published study [25]). Significance was evaluated at $p < 0.05$ for all tests. Mean separation was accomplished with Fisher's protected LSD test. All analyses were conducted using the Statistical Analysis Systems ver. 9.4 (SAS Institute, Cary, NC, USA).

3. Results

Cropping system significantly affected virtually all aspects of potato crop growth, nutrient, and yield characteristics. Effects also varied somewhat from year to year, depending on environmental conditions, but generally showing consistent trends by cropping system over time. The interaction of irrigation (whether irrigated or not irrigated) and cropping system was significant ($p < 0.05$) for most measured parameters, so for those cases, results are presented separately for irrigated and non-irrigated treatments. When irrigation by cropping system interaction was not significant, data are presented for cropping systems over both irrigation regimes.

3.1. Tuber Yield

Under non-irrigated (rainfed) conditions, the soil improving (SI) system, which included yearly compost amendments, resulted in the highest total and marketable yields of all cropping systems, showing significantly higher yields than the standard 2 y (SQ) rotation and non-rotation (PP) controls in all years, with values ranging from 34 to 44 Mg ha^{-1} and 26–35 Mg ha^{-1}, for total and marketable yield, respectively, which represented increases of 14 to 60% and 15 to 93% over those from SQ and PP systems (Table 3). The disease-suppressive (DS) system also resulted in higher total and marketable yields than PP in most years, and the SC and SQ systems in some years, whereas PP consistently resulted in the lowest overall yields of all systems. Although yields for SC remained relatively low in the early years of the study (representing the first full rotation cycle, 2006–2008), by the second rotation cycle (2009–2010), yields for SC averaged greater than both SQ and PP systems, by 12 to 23%. When averaged over all five years, all cropping systems significantly increased both total and marketable yield over PP, and DS also increased yield relative to SC and SQ, but SI produced significantly higher overall yields than all other systems, with increases in total yield averaging 41% higher than PP and 30% higher than SC and SQ (Figure 1).

Table 3. Effect of different cropping systems on total and marketable (tubers >114 g each) potato tuber yield over five field seasons (2006–2010) under irrigated (Irr) and non-irrigated (Non-irr) conditions.

	Tuber Yield (Mg/ha)									
	2006		**2007**		**2008**		**2009**		**2010**	
Treatment [x]	**Non-Irr**	**Irr**	**Non-Irr**	**Irr**	**Non-Irr**	**Irr**	**Non-Irr**	**Irr**	**Non-Irr**	**Irr**
Total yield										
SI	41.5 a [y]	43.3 ab	44.2 a	43.0 ab	33.9 a	33.9 ab	34.1 a	32.0 c	35.1 a	40.9 a
DS	36.6 ab	44.7 a	35.6 b	44.9 a	31.4 ab	36.5 a	28.1 bc	39.3 a	30.6 b	39.4 ab
SC	27.9 c	37.1 c	33.1 b	39.0 bc	30.5 ab	37.1 a	30.6 ab	36.7 b	25.5 c	37.7 abc
SQ	34.5 b	44.4 a	31.4 bc	39.3 bc	29.7 b	32.7 bc	26.7 c	32.0 c	22.0 d	35.4 c
PP	32.4 bc	38.1 bc	27.8 c	34.0 c	22.8 c	29.6 c	25.1 c	33.7 c	25.0 cd	36.5 bc
LSD (p = 0.05)	5.1	5.7	4.8	5.3	3.4	3.8	3.8	2.3	3.5	3.6
Avg.	34.6	41.5 * [z]	34.4	40.0*	29.5	34.0 *	28.8	34.7 *	27.6	38.0 *
Marketable yield										
SI	32.0 a	34.3 a	35.4 a	33.9 ab	28.1 a	27.2 a	27.9 a	26.8 b	26.3 a	30.7 ab
DS	29.3 ab	34.7 a	25.6 b	35.9 a	24.8 ab	29.3 a	22.3 bc	33.4 a	23.3 a	33.4 a
SC	21.2 c	29.5 a	22.9 b	28.6 bc	23.0 c	27.7 a	24.9 ab	28.5 b	17.6 b	33.2 a
SQ	25.4 bc	35.7 a	23.7 b	30.7 bc	24.4 bc	25.5 ab	21.7 bc	27.4 b	13.6 b	28.2 b
PP	22.8 c	29.1 a	18.8 c	25.2 c	16.2 d	21.6 c	17.9 c	25.8 b	16.5 b	29.1 b
LSD (p = 0.05)	5.9	7.3	3.8	6.3	3.5	4.5	5.4	3.7	4.8	3.2
Avg.	26.2	32.7 *	25.5	30.9 *	23.3	26.3	22.9	28.4 *	19.4	30.9 *

[x] SI = soil improving, SC = soil conserving, DS = disease suppressive, SQ = status quo, PP = continuous potato systems. [y] Values within columns for each yield type followed by the same letter are not significantly different from each other based on ANOVA and Fisher's protected LSD test (p < 0.05). [z] Mean values for irrigated treatments (Irr) followed by an asterisk are significantly greater than their corresponding non-irrigated (Non-irr) mean value within each year based on ANOVA and Fisher's protected LSD test.

Under irrigated conditions, yield (both total and marketable) in all cropping systems (except SI) increased compared to non-irrigated conditions. DS resulted in the numerically highest yields in most years, ranging from 36 to 45 Mg/ha and 29 to 36 Mg/ha for total and marketable yield, respectively, although values were generally comparable to SI or SC in individual years (Table 3). SI and SC increased total yield relative to PP in most years and SQ in some years. When averaged over all five years, again, all cropping systems increased yield relative to PP, but now DS resulted in significantly higher yields than all other systems, averaging increases of 19 and 26% over PP and 11 and 13% over SQ for total and marketable yield, respectively (Figure 1). The combined effect of irrigation and cropping system is realized when noting that DS with irrigation increased total and marketable yield by an average of 54 and 82%, respectively, over non-irrigated PP and by 42 and 54%, respectively, over non-irrigated SQ (Figure 1).

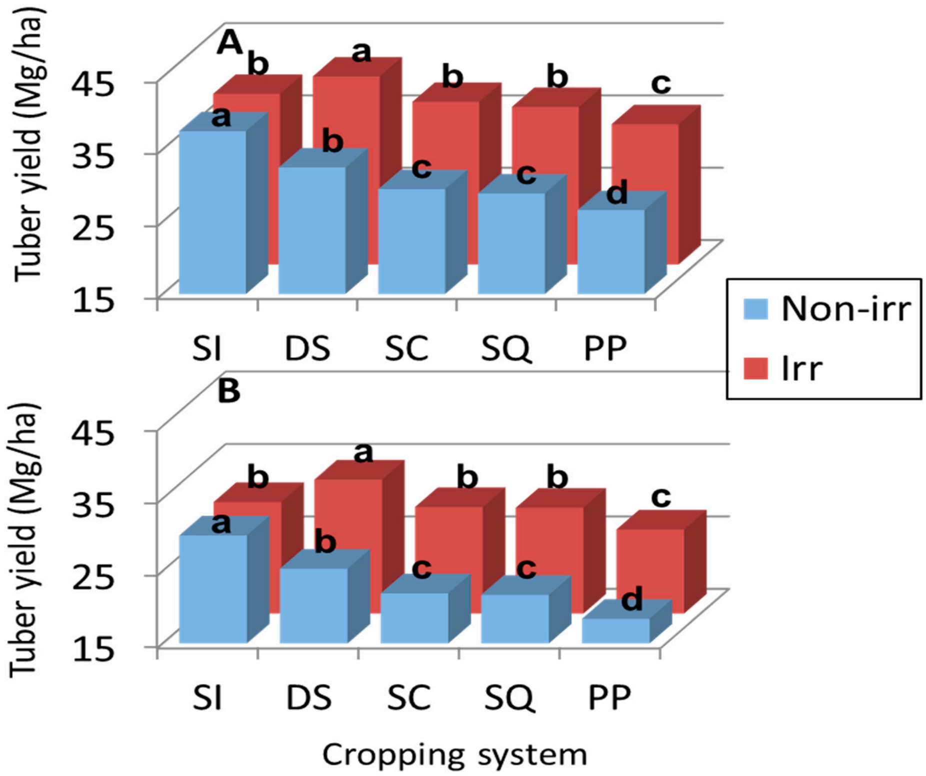

Figure 1. Effects of cropping system (SQ—standard rotation, SC—soil conserving, SI—soil improving, DS—disease suppressive, and PP—nonrotation control) and irrigation (Non-irr = Non-irrigated and Irr = Irrigated) on average (**A**) total and (**B**) marketable tuber yield over a 5 year period (2006–2010). Bars topped by the same letter within each irrigation regime are not significantly different from each other based on ANOVA and Fisher's protected LSD test ($p < 0.05$).

3.2. Tuber Size and Quality

On average, under non-irrigated conditions, SI resulted in the largest percentage of tubers in the large (228–342 g) and extra-large (>342 g) size classes, accounting for a combined 51% of all tubers compared to 29 to 35% in all other cropping systems, representing an increase of 60% relative to PP (Figure 2A). The largest individual size class for all but the SI system was the medium size class (115–227 g), accounting for 37 to 44% of the total (compared to 29% for SI). PP also resulted in the largest percentage of small-sized tubers (<114 g), comprising 31% of the total, compared to 26% for SC and SQ, and 20–22% for DS and SI systems. This resulted in PP having the lowest overall percentage of marketable tubers (comprising all size classes greater than small), at 68% for PP vs. 80 and 78% for SI and DS, and 74% for SC and SQ (Figure 2A).

Under irrigated conditions, the relative proportion of large and extra-large tubers increased for all cropping systems (except SI) relative to non-irrigated conditions, with all cropping systems still demonstrating significantly greater percentages of both size classes combined than PP (48 to 54% vs. 43% for PP) (Figure 2B). The large size class also constituted the largest individual size class for all cropping systems (36 to 39% of total). Once again, PP also resulted in the overall greatest proportion of small sized tubers, accounting for 23% of the total, which was significantly greater than the 18% in DS. Overall, percentage of marketable tubers was highest for DS (82%), significantly greater than PP, with the lowest percentage (77%), and in-between for the other cropping systems (79–81%) (Figure 2B).

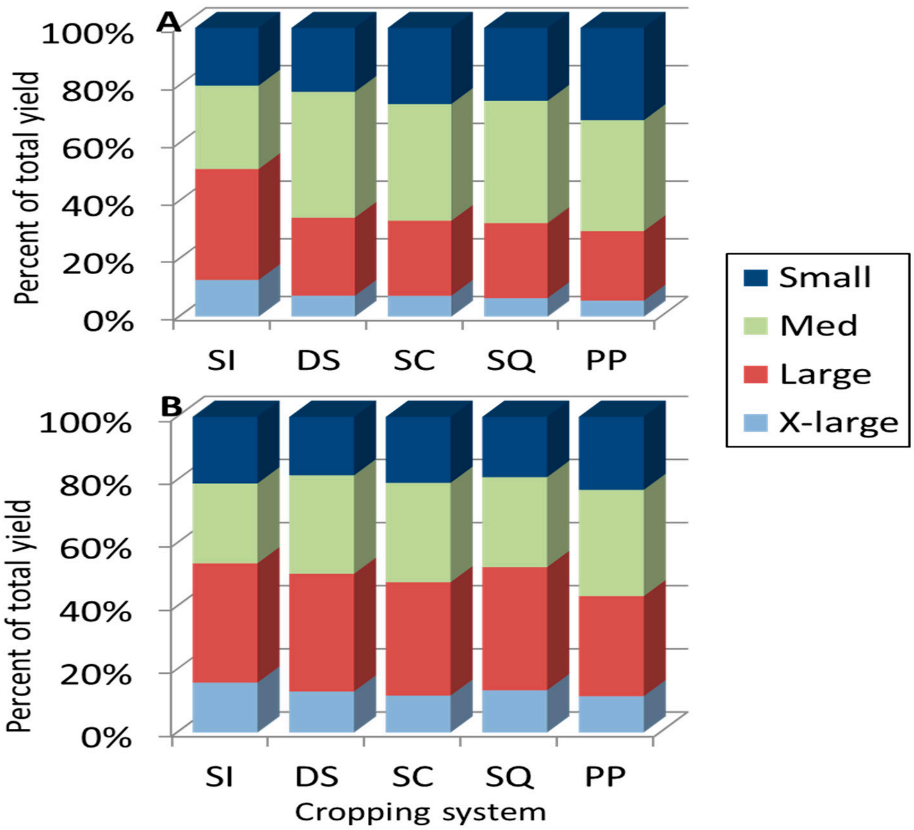

Figure 2. Effect of cropping system on average tuber size class distribution under (**A**) non-irrigated and (**B**) irrigated conditions as averaged over five cropping seasons (2006–2010).

Under non-irrigated conditions, the proportion of severely misshapen tubers was significantly lower for all cropping systems than the non-rotation control PP when averaged over all cropping years (9 to 14% vs. 20% for PP), but was not statistically different among cropping systems (Figure 3). Under irrigated conditions, DS maintained the overall lowest percentage of misshapen tubers (12.1%), significantly lower than SI and PP (20 to 22%), and SC and SQ were also lower than PP (at 15%) (Figure 3).

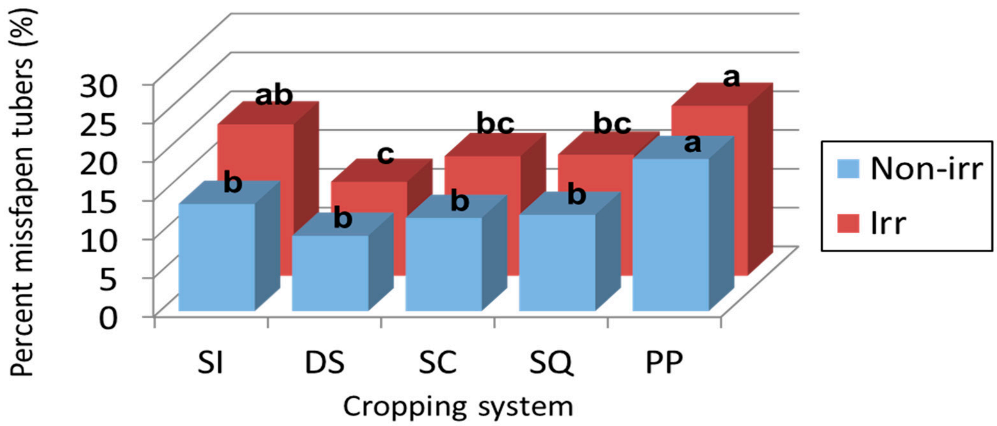

Figure 3. Effect of cropping system (SQ—standard rotation, SC—soil conserving, SI—soil improving, DS—disease suppressive, and PP—non-rotation control) and irrigation (Non—Non-irrigated and Irr—Irrigated) on average percentage of severely misshapen tubers as averaged over a 5 year period (2006–2010). Bars topped by the same letter within each irrigation regime are not significantly different from each other based on ANOVA and Fisher's protected LSD test ($p < 0.05$).

Tuber specific gravity varied somewhat from year to year, with generally lower values in 2010 and higher values in 2009 than other years. Although, generally, there were no significant effects due to irrigation, the interaction between irrigation and cropping system was significant ($p < 0.05$), so results are presented separately for irrigated and non-irrigated conditions. Under non-irrigated conditions, there was no effect of cropping system on specific gravity in 2007 and 2009, but in 2008 and 2010, SI resulted in lower specific gravity than all other cropping systems (Table 4). SC also showed lower specific gravity than PP and SQ in 2010. Over all years, SI and SC averaged slightly lower specific gravity than the other cropping systems. Under irrigated conditions, PP resulted in higher specific gravity than all other systems in 2008, 2009, and 2010, and both PP and SQ demonstrated higher specific gravity than SI in 2007. SI generally resulted in lower specific gravity than most cropping systems. Averaged over all years, PP resulted in higher specific gravity and SI lower specific gravity than all other cropping systems (Table 4).

Table 4. Effect of different cropping systems on tuber specific gravity over four field seasons (2007–2010) under irrigated (Irr) and non-irrigated (Non-irr) conditions.

	Tuber Specific Gravity									
	2007		2008		2009		2010		Mean	
Treatment [y]	Non-Irr	Irr	Non-Irr	Irr	Non-Irr	Irr	Non-Irr	Irr	Non-Irr	Irr
SI	1.083 a [z]	1.082 b	1.082 b	1.083 c	1.088 a	1.087 b	1.074 c	1.071 c	1.082 b	1.081 c
DS	1.085 a	1.086 ab	1.087 a	1.085 b	1.086 a	1.092 ab	1.079 ab	1.075 b	1.084 a	1.085 b
SC	1.082 a	1.086 ab	1.085 a	1.085 b	1.086 a	1.090 b	1.077 b	1.074 bc	1.082 b	1.084 b
SQ	1.085 a	1.087 a	1.086 a	1.084 c	1.087 a	1.089 b	1.080 a	1.075 b	1.084 a	1.084 b
PP	1.082 a	1.087 a	1.087 a	1.088 a	1.087 a	1.096 a	1.080 a	1.078 a	1.084 a	1.087 a
LSD	0.004	0.005	0.004	0.002	0.003	0.005	0.002	0.003	0.002	0.002

[y] SI = soil improving, SC = soil conserving, DS = disease suppressive, SQ = status quo, PP = continuous potato systems. [z] Values within columns followed by the same letter are not significantly different from each other based on ANOVA and Fisher's protected LSD test ($p < 0.05$).

3.3. *Crop Growth Assays*

3.3.1. Leaf Area Duration and Chlorophyll Content

Emergence was uniformly high across years and cropping systems (94 to 98%), with no significant effects due to irrigation or among cropping systems (data not shown). Leaf area index values collected over time within each cropping season were converted to leaf area duration (LAD) to provide an overall measure of leaf area and biomass production for each cropping system. Under non-irrigated conditions, SI produced significantly greater LAD in 2007–2009 than all other cropping systems, with both SI and DS producing higher LAD than others in 2006 (Table 5). In 2008, PP resulted in lower LAD than all other systems. Averaged over all years, SI resulted in higher LAD than all other systems, and DS in higher LAD than the remaining systems, with SI averaging 60 to 66% higher than SQ and PP values. Irrigation significantly increased LAD values in all years and in all cropping systems except SI. Under irrigated conditions, there were fewer differences among cropping systems, but SI resulted in greater LAD than SC and PP in 2006, and PP resulted in lower LAD than all other systems in 2008. When averaged over all years, SI and DS resulted in significantly higher LAD than SC and PP (by about 13%), and LAD for PP was also lower than for SQ (Table 5).

Table 5. Effect of different cropping systems on leaf area duration and chlorophyll content (SPAD assessment) over four field seasons (2006–2009) under irrigated (Irr) and non-irrigated (Non-irr) conditions.

	2006		**2007**		**2008**		**2009**		**Mean (2006–2009)**	
Treatment [x]	**Non-Irr**	**Irr**	**Non-Irr**	**Irr**	**Non-Irr**	**Irr**	**Non-Irr**	**Irr**	**Non-Irr**	**Irr**
Leaf area duration										
SI	194.1 a [y]	228.2 a	244.2 a	216.6 a	224.3 a	221.8 a	184.6 a	176.9 a	211.7 a	210.9 a
DS	166.5 a	204.2 ab	173.6 b	222.7 a	174.6 b	232.9 a	120.0 b	185.9 a	158.2 b	211.4 a
SC	117.2 b	181.2 b	149.1 b	190.6 a	152.1 c	216.9 a	115.8 b	170.5 a	133.5 c	189.8 bc
SQ	129.6 b	214.3 ab	141.0 b	213.1 a	152.2 c	237.3 a	108.1 b	158.7 a	132.7 c	205.8 ab
PP	123.2 b	178.5 b	169.5 b	226.4 a	118.0 d	187.4 b	98.7 b	156.0 a	127.3 c	187.1 c
LSD	42.6	46.4	30.9	42.9	18.9	28.9	41.6	31.2	14.8	18.0
Avg.	146.1	201.3 * [z]	175.5	214.8 *	163.8	219.3 *	125.4	169.6 *	152.6	201.1 *
Chlorophyll content (SPAD)										
SI	39.9 a	39.0 a	42.6 a	42.6 a	37.0 a	37.1 ab	38.8 a	40.4 ab	39.6 a	39.8 a
DS	39.5 a	38.2 a	39.9 b	41.8 ab	34.6 bc	36.0 bc	37.8 ab	40.2 ab	38.0 b	39.1 b
SC	38.4 a	38.1 a	38.5 b	41.7 ab	33.9 c	36.4 ab	37.2 b	40.3 ab	37.0 c	39.2 b
SQ	39.6 a	39.0 a	40.0 b	42.7 a	35.6 b	37.3 a	38.0 ab	40.7 a	38.3 b	39.9 a
PP	39.4 a	38.6 a	38.7 b	40.8 b	34.2 c	34.9 c	37.4 b	39.6 b	37.4 c	38.5 c
LSD	1.0	1.1	1.4	1.2	1.2	1.2	1.3	1.1	0.6	0.5
Avg.	39.4	38.6 *	39.9	41.9 *	35.1	36.4 *	37.8	40.2 *	38.0	39.3 *

[x] SI = soil improving, SC = soil conserving, DS = disease suppressive, SQ = status quo, PP = continuous potato systems. [y] Values within columns for each parameter followed by the same letter are not significantly different from each other based on ANOVA and Fisher's protected LSD test ($p < 0.05$). [z] Mean values for irrigated treatments followed by an asterisk are significantly greater than their corresponding non-irrigated mean value within each year based on ANOVA and Fisher's protected LSD test.

Leaf chlorophyll content as estimated by SPAD determinations was also affected by both cropping system and irrigation in all years but 2006 (Table 5). Under non-irrigated conditions, SI resulted in higher chlorophyll content than all other cropping systems in 2007 and 2008, and higher than SC and PP in 2009. Irrigation generally increased chlorophyll content across cropping systems. Under irrigated conditions, PP resulted in lower chlorophyll content than SI and SQ in 2007; SI, SC, and SQ in 2008; and SQ in 2009. Averaged over all years, SI and SQ resulted in higher chlorophyll content and lower PP content than all other cropping systems (Table 5).

3.3.2. Root, Shoot, and Tuber Biomass

Biomass of above- and below-ground plant parts, such as root, shoot, and tuber biomass, collected in August of each year demonstrated some differences due to both cropping system and irrigation, although there was no significant effect on root biomass or tuber biomass in 2007. Under non-irrigated conditions, SI resulted in greater root biomass than PP in 2008 and greater than all other cropping systems in 2009, as well as greater than all cropping systems when averaged over all three years (Table 6). DS also resulted in greater root biomass than PP over all years combined. Under irrigated conditions, root biomass increased in 2008 and 2009 overall, relative to no irrigation, as well as across all years when averaged together. SC resulted in greater root biomass than SQ and PP in 2008, as well as greater root biomass than PP when averaged over all years. Shoot biomass showed the greatest differences among cropping systems under non-irrigated conditions, with SI resulting in greater shoot biomass than all other cropping systems in all three years, as well as when averaged over all years (Table 6). Under irrigated conditions, SI resulted in greater shoot biomass than PP in 2008 and all other cropping systems in 2009, as well as greater shoot biomass than all other cropping systems when averaged over all years. PP also resulted in lower shoot biomass than SI, DS, and SC when averaged over all years (Table 6). Tuber biomass was only significantly affected by cropping system under irrigated conditions in 2008 and under non-irrigated conditions in 2009, with DS resulting in higher tuber biomass than SI and SQ in 2008 and PP resulting in higher biomass than SI in 2009 (Table 6). Averaged over all three years, DS resulted in higher tuber biomass than SI under both irrigated and non-irrigated conditions, and higher tuber biomass than SQ under irrigation.

Table 6. Effect of different cropping systems on potato plant root and shoot biomass (dry wt) over three field seasons (2007–2009) under irrigated and non-irrigated conditions.

	Biomass (Mg dry wt/ha)							
	2007		2008		2009		Mean (2007–2009)	
System [y]	**Non-Irr**	**Irrigated**	**Non-Irr**	**Irrigated**	**Non-Irr**	**Irrigated**	**Non-Irr**	**Irrigated**
Root Biomass								
SI	0.136 a [z]	0.106 a	0.168 a	0.198 ab	0.188 a	0.190 a	0.164 a	0.165 ab
DS	0.118 a	0.098 a	0.140 ab	0.211 ab	0.134 b	0.176 a	0.131 b	0.161 ab
SC	0.104 a	0.120 a	0.130 ab	0.236 a	0.138 b	0.180 a	0.124 bc	0.179 a
SQ	0.086 a	0.090 a	0.124 ab	0.168 b	0.136 b	0.194 a	0.115 bc	0.151 ab
PP	0.076 a	0.108 a	0.100 b	0.144 b	0.136 b	0.166 a	0.104 c	0.139 b
LSD (p = 0.05)	0.056	0.042	0.051	0.064	0.025	0.041	0.024	0.027
Shoot biomass								
SI	3.37 a	3.56 a	3.36 a	3.71 a	3.62 a	4.00 a	3.44 a	3.76 a
DS	2.55 b	3.45 a	2.03 c	2.73 ab	1.98 b	2.93 b	2.19 b	3.04 b
SC	2.16 b	3.25 a	1.96 c	3.01 ab	1.88 b	2.85 b	1.97 b	3.04 b
SQ	2.26 b	3.21 a	2.64 b	2.79 ab	1.76 b	2.43 b	2.26 b	2.81 bc
PP	1.86 b	3.06 a	1.89 c	2.34 b	2.12 b	2.30 b	1.96 b	2.56 c
LSD (p = 0.05)	0.68	0.91	0.49	0.98	0.44	0.67	0.33	0.41
Tuber biomass								
SI	3.19 a	3.62 a	2.44 a	1.88 bc	3.35 b	3.85 a	2.99 b	3.12 b
DS	3.58 a	4.00 a	3.06 a	3.11 a	4.51 ab	4.87 a	3.72 a	3.99 a
SC	3.69 a	3.75 a	3.14 a	2.80 ab	4.03 ab	4.43 a	3.62 ab	3.66 ab
SQ	3.07 a	4.24 a	2.81 a	1.79 c	3.92 ab	3.75 a	3.26 ab	3.26 b
PP	3.53 a	3.64 a	2.72 a	2.41 abc	4.63 a	5.02 a	3.63 ab	3.69 ab
LSD (p = 0.05)	1.08	1.71	1.04	0.91	1.10	1.32	0.65	0.59

[y] SI = soil improving, SC = soil conserving, DS = disease suppressive, SQ = status quo, PP = continuous potato systems. [z] Values within columns for each parameter followed by the same letter are not significantly different from each other based on ANOVA and Fisher's protected LSD test ($p < 0.05$).

3.3.3. Plant Tissue Elemental Analyses

Shoot tissue concentrations were significantly affected by cropping system for all nutrient elements measured (except Boron), but were generally not affected by irrigation (and no irrigation by cropping system interaction), except for slight increases in P and B, and a decrease in Zn observed in irrigated vs. non-irrigated systems (data not shown). SI resulted in higher shoot tissue concentrations of P and K, and SI and SQ for N, than all other cropping systems, whereas PP tended to have the lowest concentrations of N and P (Table 7). However, PP and SC tended to have higher and SI lower shoot tissue concentrations of Ca and Mg. For Mn, DS averaged the highest and SI the lowest shoot tissue concentration, and for the metals Fe, Al, Cu, and Zn, SI averaged lower and PP higher concentrations than most other cropping systems (Table 7).

Overall, cropping system and irrigation did not significantly affect root tissue nutrient concentrations for all elements measured, except for a slight increase in P for SI relative to the other cropping systems, and higher K, Mg, and Zn levels in non-irrigated vs. irrigated systems (data not shown). For tuber concentrations, irrigation only significantly affected N, Mg, and B concentrations, with irrigation resulting in slightly lower N and Mg concentrations, and higher B concentration than non-irrigated (data not shown). Overall, tuber tissue concentrations were substantially lower than shoot tissue concentrations for all elements, except for P, which were higher in tuber tissue.

Table 7. Effect of different cropping systems on shoot tissue elemental composition (2008 data).

	Elemental Composition									
Treatment [y]	**N**	**P**	**K**	**Ca**	**Mg**	**Mn**	**Fe**	**B**	**Cu**	**Zn**
	%					ppm				
Shoot tissue										
SI	3.95 a [z]	0.235 a	5.47 a	1.21 c	0.834 c	262.9 c	165.8 b	27.1 a	7.77 b	113.4 b
DS	3.58 b	0.185 cd	4.67 b	1.24 bc	0.893 bc	422.1 a	199.0 ab	25.4 a	8.88 b	127.0 ab
SC	3.53 bc	0.198 bc	4.68 b	1.25 bc	0.861 bc	359.9 b	181.8 b	25.2 a	9.94 ab	129.8 a
SQ	3.83 a	0.199 b	4.32 b	1.35 a	0.929 ab	389.6 ab	240.0 a	26.2 a	9.25 ab	128.8 ab
PP	3.32 c	0.181 d	4.39 b	1.32 ab	0.949 a	355.5 b	207.0 ab	24.9 a	11.27 a	130.9 a
LSD	0.23	0.014	0.38	0.088	0.075	54.0	50.0	2.6	2.05	14.9
Tuber tissue										
SI	1.74 a	0.260 a	2.49 a	0.043 a	0.107 ab	17.2 ab	19.5 ab	5.50 a	8.00 a	17.5 a
DS	1.66 a	0.210 d	2.24 b	0.032 c	0.105 ab	19.6 a	24.1 a	4.76 a	8.14 a	15.1 c
SC	1.70 a	0.246 ab	2.29 b	0.033 c	0.104 ab	18.6 ab	18.9 b	4.97 a	8.44 a	16.1 bc
SQ	1.67 a	0.222 cd	2.15 b	0.038 b	0.102 b	18.7 ab	18.2 b	5.18 a	7.98 a	15.4 c
PP	1.72 a	0.230 bc	2.24 b	0.035bc	0.111 a	15.1 b	19.6 ab	4.86 a	8.32 a	16.7ab
LSD	0.09	0.017	0.13	0.004	0.006	3.4	4.7	0.75	0.49	1.0

[y] SI = soil improving, SC = soil conserving, DS = disease suppressive, SQ = status quo, PP = continuous potato systems. [z] Values within columns for each parameter followed by the same letter are not significantly different from each other based on ANOVA and Fisher's protected LSD test ($p < 0.05$).

Cropping system effects on tuber tissue concentration included higher concentrations of P, K, and Ca for SI than all other cropping systems, although there was no effect on N among cropping systems (Table 7). DS averaged higher tuber tissue concentrations of Mn than PP and higher concentrations of Fe and Al than SC and SQ. SI registered the highest tuber concentration of Zn and PP the highest concentration of Mg among cropping systems.

3.4. Parameter Correlations

Total and marketable tuber yields were highly correlated ($p < 0.001$) with crop growth parameters such as LAD, chlorophyll content, shoot biomass, and total biomass, and weakly correlated ($p < 0.05$) with the soil physical/chemical parameter soil C/N ratio across all samples (irrigated and non-irrigated conditions) and all years. Total and marketable yields were also correlated ($p < 0.05$) with soil moisture, total soil C, soil N, and soil ammonium (NH_4) concentration sampled in spring under non-irrigated, but not under irrigated, conditions. Marketable yield was also correlated with potentially mineralizable N and negatively correlated with bulk density under non-irrigated, but not under irrigated, conditions. The percentage of large and extra-large tubers was correlated with LAD, chlorophyll content, root and shoot biomass, soil moisture, aggregate stability, active C, soil C and N, POM C and N, potentially mineralizable N, and NO_3 and NH_4 concentrations, and negatively correlated with bulk density under both irrigated and non-irrigated conditions across all years.

4. Discussion

In this research, multiple individual soil health management practices were combined into cropping systems with specific management goals of soil conservation, soil improvement, and disease suppression, and effects on crop growth, nutrition, and tuber yield and quality were assessed over up to five full cropping seasons (and after cropping systems in place for 3 to 7 years) under both non-irrigated (rainfed) and irrigated conditions. Combined data from all five seasons demonstrated that cropping system significantly affected virtually all of the crop and plant characteristics measured, ranging from crop growth (photosynthetic potential and biomass) and tissue nutrient concentration to potato tuber yield and quality, with the soil improving (SI) system, which included compost amendments, cover crops, and reduced tillage in a 3 y rotation, producing the greatest overall effects and improvements in these crop production parameters, particularly without irrigation. Irrigation effects were also significant for most parameters. This research demonstrated that improved cropping systems can substantially enhance characteristics associated with potato crop productivity.

Concurrent research on these same cropping systems over the same years documented the system effects on soil physical, chemical, and biological properties, and that effects tended to increase over time [24,25]. In these studies, all rotations increased aggregate stability, water availability, microbial biomass C, and total C and N compared to no rotation (PP), and the 3 y systems (SI, SC, DS) increased aggregate stability relative to the 2 y system (SQ). Additionally, the 3 y systems with reduced tillage (SI and SC) increased water availability and reduced bulk density relative to the other systems. However, the SI system resulted in greater increases in total and particulate organic matter (POM) C and N; active C; microbial biomass C; water availability; CEC; concentrations of P, K, Ca, Mg, and S; and lower bulk density than all other cropping systems [24,25]. SI was also shown to increase microbial activity and greatly affect soil microbial community characteristics, whereas PP showed the lowest microbial activity, with the others in between [20,21]. These changes all constitute parameters associated with improved soil health.

In the present study, under non-irrigated conditions, all crop rotations increased total and marketable tuber yields over no rotation (PP), but the SI system resulted in the highest tuber yield of all systems (both total and marketable), averaging 30 to 40% higher than SQ and PP systems over all years. Yield differences were greatest in the drier years (2007 and 2010), when SI yields were 40–90% higher than SQ and PP. In addition, SI resulted in the highest percentage of large and extra-large size-class tubers, and fewer small or under-sized tubers. It is also noteworthy that with irrigation, all cropping systems, with the exception of SI, produced substantially higher yields than their non-irrigated counterpart, with total and marketable yields averaging 27 and 37% higher, respectively, demonstrating that only SI produced comparable (and high) yields under both irrigated and non-irrigated conditions. These yield effects indicate the importance of adequate soil water in potato production and, as has also been previously demonstrated, that in most years, supplemental irrigation is needed in Maine to increase productivity [29,31]. However, the data also strongly suggest that the yield increases observed in SI are related to soil health improvements associated with increased water-holding capacity and plant-available water. Thus, the improvements in soil characteristics, and particularly the increased organic matter and ability to store and hold available water provided by the compost amendments, apparently enabled SI to produce higher yields when not irrigated than all other cropping systems. Essentially, under these conditions, the improvements resulting from the compost amendments -effectively substituted for water additions through irrigation in these studies. This aspect was noted and explored in previous research examining the economics of potentially using compost amendments as an alternative to irrigation [34]. In other research, compost amendments have been shown to provide similar increases in organic matter, water availability, various soil quality parameters, and generally higher tuber yields [5,14,35,36], although in some cases, tuber yields were not significantly increased with compost amendments even when there was substantial improvement in soil quality parameters [37,38]. Organic matter amendments have been shown to improve soil structural stability primarily through increases in aggregate stability, as well as improvements in bulk density, aeration, porosity, and water movement [39–42].

There are many aspects and changes in soil characteristics involved with the compost amendments and other factors within the SI system, and thus the specific cause of the yield increases observed cannot be conclusively determined. However, based on the results observed and the characteristics of these systems, it is apparent that improvements in properties associated with the ability to store and hold soil water were at least partially, if not primarily, responsible for the yield increases observed in the SI system, rather than such aspects as nutritional improvements. First, all systems were supplied with adequate (above optimal NPK) fertilization so as not to limit productivity based on numerous studies in this area [29–33]. Additional NPK fertility above these levels provided by the compost amendments would not be expected to increase yield further, as studies have indicated depressed yields, not increased yields, with above optimal fertilizer additions [29–33]. Most importantly, SI had higher yields than other systems when not irrigated, but no improvement with irrigation, even though all other systems showed increased yields when irrigated. If yield increases were primarily related to increased nutrition, then we would expect to observe an irrigation effect, as with all other systems, but in SI, comparable yields were produced under irrigated and non-irrigated conditions. Additionally, under irrigated conditions, SI would be expected to produce higher yields than the other systems, but again, this was not observed, thus further indicating that added nutrition was not the primary cause of increased yields with SI. Overall, differences in water availability appeared to explain a substantial part of the cropping system yield differences observed. Under irrigated conditions, DS produced the highest overall yields, while PP still resulted in lower yields than all other cropping systems. Interestingly, these irrigation effects on yield were observed even in 2009, a year in which no irrigation treatments were applied (as were not needed), yet effects were still observed, possibly a result of cumulative beneficial effects due to a history of previous irrigation.

The DS system also resulted in overall significant increases in total and marketable yield relative to SC, SQ, and PP under non-irrigated conditions. These increases were presumably due to the beneficial effects of the added green manure and cover crops in reducing potential pathogens and soilborne diseases, and maintaining various soil health parameters, as has been observed in other potato systems [12,43,44]. As previously reported, DS resulted in lower incidence and severity of multiple soilborne diseases (including stem canker, black scurf, and common scab), as well as significant effects on soil microbial community characteristics, but more modest effects on soil chemical and biological parameters [20,21]. The SC system, however, despite increased rotation length, use of cover crops, and reduced tillage, resulted in comparable tuber yield to the standard 2 y SQ rotation through most years of this study, although it did show indications of higher yields than SQ in the later years (following the second full rotation cycle). Other researchers have also noted that significant effects due to increased rotation length and cover crops alone may take several years to develop [6,45,46], and this was also indicated in the overall comparable soil properties observed for SC and SQ through the early years of the study [24,25].

Overall, average yield values for DS, SC, and SQ under non-irrigated conditions were comparable to average state-wide values for commercial production in Maine for this period (~32 Mg/ha, 2006–2010) [47], whereas SI averaged higher, and PP lower than average, as the majority of commercial production in Maine is not irrigated. However, under irrigated conditions, all cropping systems resulted in yields above the state-wide averages (by 8 to 28%).

Specific gravity is an important quality characteristic for processing potatoes, as it represents the dry matter content of tubers. Higher specific gravity means higher dry matter content, which produces lighter color, absorbs less oil, and requires fewer tubers and less time to produce the same yield of finished product (thus less costly to produce) [48]. Specific gravity varied somewhat among cropping systems, with PP resulting in the overall highest values, and SI resulting in lower values. However, acceptable specific gravity values for Russet Burbank of 1.082 or higher (representing total solids content of >21.5%) were observed for all cropping systems in all years except 2010, which was the warmest and driest summer, with higher than normal temperatures and lower than normal rainfall observed throughout July, August, and September. High temperatures and water stress are known to depress specific gravities, as well as excessive water and/or fertilization [49,50]. The slightly lower specific gravity observed in SI is probably due to the higher organic matter content and lower bulk density of those soils, as organic amendments may also reduce specific gravity [36]. Although there was no overall irrigation effect on specific gravity, there was a significant interaction between cropping system and irrigation, and it appears that for most of the systems, there was a slight increase in specific gravity associated with irrigation for most systems, but a slight decrease in SI, resulting in no overall effect.

Under non-irrigated conditions, SI also resulted in the greatest photosynthetic potential, as represented by the leaf area index, leaf area index over time (leaf area duration—LAD), and leaf chlorophyll content. Yields are closely associated with the ability of a plant to intercept solar radiation and its efficiency in accumulating dry matter. LAD has been shown to be more closely related to yield than LAI and other indicators of leaf area [51]. SPAD readings are closely related to actual chlorophyll content and have been used as an indicator of leaf N content, but recent research indicates that the relationship between SPAD readings and Leaf N content can be greatly affected by environmental conditions and crop species [52]. SI also resulted in greater overall root and shoot biomass than the other cropping systems, demonstrating the impact of the improved soil quality parameters for SI on all aspects of crop growth dynamics. Previous research has also demonstrated that large additions of organic matter can dramatically affect these growth parameters [36,53]. Surprisingly, however, SI resulted in overall lower tuber biomass than DS, but it must be taken into account that the biomass measurements were made in early August, when tubers were first developing, and do not represent any potential effects on yield. Although DS resulted in overall greater LAD than the remaining systems, and greater chlorophyll content than SQ and PP, there were fewer differences among the other cropping systems for biomass measurements under non-irrigated conditions, although PP generally resulted in lower values for most parameters. Irrigation resulted in overall increases in LAD and chlorophyll content for all systems, but irrigation effects on biomass were inconsistent. Although averages over all three years of biomass data indicated overall increases due to irrigation, individual years varied. There were some differences among cropping systems overall, including greater root biomass in SC than PP, greater shoot biomass in SI than all systems, and greater tuber biomass in DS than SI and SQ, but again, effects were variable between years. These differences reflect the generally more favorable conditions for biomass growth under irrigated conditions.

SI also resulted in generally higher levels of N, P, and K in above-ground shoot and tuber tissues, but lower concentrations of Ca, Mg, and Mn in shoot tissue, as well as generally lower concentrations of Fe, Cu, and Zn, relative to most other cropping systems. This observation indicated that SI management did not always increase the levels of these micronutrients, even though soil levels of these nutrients were generally increased in SI [24,25]. However, this observation was consistent with studies of other cropping systems amended by organic fertilizers. For example, application with poultry litter resulted in a greater concentration of extractable soil P, K, Ca, Mg, Cu, Zn, and Na. However, these increases did not always result in greater concentrations of these elements in cotton plant parts [54,55]. SQ and PP tended to have higher Ca and Mg concentrations in shoot tissue, as well as higher Fe, Cu, and Zn, than most other systems. Overall, tissue concentrations for all major nutrient elements (N, P, K, Ca, Mg) for all cropping systems were within the normal (sufficient level) ranges previously observed and reported for potato leaf and tuber tissues [56,57].

Although only one potato variety, Russet Burbank, which is the predominant processing variety grown commercially in the northeast, was used in this study, observed results should be generally applicable to other potato varieties as well. Previous studies in this region have indicated similar responses to rotations, amendments, and fertilization in multiple different potato varieties [29–32,36], and improvements in soil health have been associated with increases in yield across not only different potato varieties but many different crops as well [4,6,12–15,44].

Overall, this study demonstrated that incorporating soil health management practices into integrated cropping systems can greatly affect crop growth and productivity parameters, and can be used to improve crop growth and yield, in addition to benefits in soil health and other soil properties. The integration of practices such as extending crop rotations, use of cover crops and green manures, reduced tillage, and, particularly, organic amendments, into existing, modified, and enhanced potato cropping systems may provide the basis for greater sustainability and productivity in potato production systems. This study also demonstrated that development of improved cropping systems can substantially enhance productivity from the standard cropping system currently used throughout Northeastern US for potato production. The SI system, which incorporated large organic amendments along with a longer rotation period, use of cover crops, and reduced tillage, resulted in substantial effects and improvements in crop growth and yield, particularly under non-irrigated conditions. Organic matter affects and influences many different soil physical, chemical, and biological properties in various ways, and has often been cited as the single most important aspect of soil health [4,58]. Characterization of the water-extractable organic matter samples within the cropping systems suggested that these management practices stimulated the decomposition of the humic fraction in the soil organic matter pool, implying healthier soil conditions with these practices than in continuous potato growth [59]. The current study further revealed that large organic matter amendments had the most immediate and substantial effects of all the cropping systems. This research also emphasized the importance of soil water, and that under normal environmental conditions during cropping seasons in Maine, irrigation provides a definite yield benefit under most cropping systems, but also that one of the benefits of the large organic amendments in SI was that it could be an effective substitute for irrigation and produce high yields without irrigation, at least under the conditions occurring during this study. Although SI and the effects of organic amendments appeared to provide the most substantial effects, the DS system, which included disease-suppressive rotation crops, green manures, crop diversity, and increased tillage (for incorporation of cover crops and green manures), also resulted in high yields (highest under irrigation) throughout, demonstrating the impact of reduced disease levels and other benefits provided by green manure crops and crop diversity. However, for the relatively short duration of this study, a small increase in rotation length, cover crops, and reduced tillage, as provided in the SC system was not sufficient to produce an overall increase in yield and growth parameters relative to the standard 2 y rotation, although by the second rotation cycle, indications of higher SC yields were evident. Additional time, or more aggressive changes, appear to be necessary to achieve enhanced productivity in this system. However, all these approaches still may provide some benefits in contributing to the overall goals of maintaining and/or improving soil health. Research is continuing to integrate the principles of these systems into more productive and economically viable enhanced cropping systems for growers in the northeast and elsewhere.

Author Contributions: Project conceptualization, methodology, and investigation, R.P.L., C.W.H., T.S.G., O.M.O. and Z.H.; formal analysis and writing original draft, R.P.L.; project administration and supervision, C.W.H.; reviewing and editing by all authors. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Acknowledgments: Many people have worked on or contributed to this research in various ways over the years of these studies, including summer workers and student aides, field crews, technicians, and colleagues. Most importantly, we would like to thank D. Cowperthwaite for managing and maintaining the field site, as well as J. Hunt, P. Pinette, E. Champaco, L. Matthiesen, G. Trusty, E. Mallory, B. LeGasse, and D. Torrey for additional technical support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Doran, J.W.; Sarrantonio, M.; Leibig, M. Soil health and sustainability. In *Advances in Agronomy*; Sparks, D.L., Ed.; Academic Press: San Diego, CA, USA, 1996; pp. 1–54.
2. Doran, J.W.; Zeiss, M.R. Soil health and sustainability: Managing the biotic component of soil quality. *Appl. Soil Ecol.* **2000**, *15*, 3–11. [CrossRef]
3. Larkin, R.P. Soil health paradigms and implications for disease management. *Annu. Rev. Phytopathol.* **2015**, *53*, 19–221. [CrossRef] [PubMed]
4. Magdoff, F.; van Es, H. *Building Soils for Better Crops*, 3rd ed.; Sustainable Agriculture Research and Education: Waldorf, MD, USA, 2009.
5. Grandy, A.S.; Porter, G.A.; Erich, M.S. Organic amendment and rotation crop effects on the recovery of soil organic matter and aggregation in potato cropping systems. *Soil Sci. Soc. Am. J.* **2002**, *66*, 1311–1319. [CrossRef]
6. Carter, M.R.; Sanderson, J.B. Influence of conservation tillage and rotation length on potato productivity, tuber disease and soil quality parameters on a fine sandy loam in eastern Canada. *Soil Tillage Res.* **2001**, *63*, 1–13. [CrossRef]
7. Mohr, R.M.; Volkmar, K.; Derksen, D.A.; Irvine, R.B.; Khakbazan, M.; McLaren, D.L.; Monreal, M.A.; Moulin, A.P.; Tomasiewicz, D.J. Effect of rotation on crop yield and quality in an irrigated potato system. *Am. J. Potato Res.* **2011**, *88*, 346–359. [CrossRef]
8. Peters, R.D.; Sturz, A.V.; Carter, M.R.; Sanderson, J.B. Influence of crop rotation and conservation tillage practices on the severity of soil-borne potato diseases in temperate humid agriculture. *Can. J. Soil Sci.* **2004**, *84*, 397–402. [CrossRef]
9. Scholte, K. Causes of differences in growth pattern, yield and quality of potatoes (*Solanum tuberosum* L.) in short rotations on sandy soil as affected by crop rotation, cultivar, and application of granular nematicides. *Potato Res.* **1990**, *33*, 181–190. [CrossRef]
10. Wright, P.J.; Falloon, R.E.; Hedderly, D. A long-term vegetable crop rotation study to determine effects on soil microbial communities and soilborne diseases of potato and onion. *N. Z. J. Crop Hortic. Sci.* **2017**, *45*, 29–54. [CrossRef]
11. Essah, S.Y.C.; Delgado, J.A.; Dillon, M.; Sparks, R. Cover crops can improve potato tuber yield and quality. *HortTechnology* **2012**, *22*, 185–190. [CrossRef]
12. N'Dayegamiye, A.; Nyiraneza, J.; Grenier, M.; Bippfubusa, M.; Drapeau, A. The benefits of crop rotation including cereals and green manure on potato yield and nitrogen nutrition and soil properties. *Adv. Crop Sci. Tech.* **2017**, *5*, 279. [CrossRef]
13. Bernard, E.; Larkin, R.P.; Tavantzis, S.; Erich, M.S.; Alyokhin, A.; Gross, S. Rapeseed rotation, compost, and biocontrol amendments reduce soilborne diseases and increase tuber yield in organic and conventional potato production systems. *Plant Soil* **2014**, *374*, 611–627. [CrossRef]
14. Blanchet, G.; Gavazov, K.; Bragazza, L.; Sinaj, S. Responses of soil properties and crop yields to different inorganic and organic amendments in a Swiss conventional farming system. *Agric. Ecosyst. Environ.* **2016**, *230*, 116–126. [CrossRef]
15. Ninh, H.T.; Grandy, A.S.; Wickings, K.; Snapp, S.S.; Kirk, W.; Hao, J. Organic amendment effects on potato productivity and quality are related to soil microbial activity. *Plant Soil* **2015**, *386*, 223–236. [CrossRef]
16. Carter, M.R.; Noronha, C.; Peters, R.D.; Kimpinski, J. Influence of conservation tillage and crop rotation on the resilience of an intensive long-term potato cropping system. *Agric. Ecosyst. Environ.* **2009**, *133*, 32–39. [CrossRef]
17. Larkin, R.P.; Griffin, T.S.; Honeycutt, C.W. Rotation and cover crop effects on soilborne potato diseases, tuber yield, and soil microbial communities. *Plant Dis.* **2010**, *94*, 1491–1502. [CrossRef]
18. Larkin, R.P.; Halloran, J.M. Management effects of disease-suppressive rotation crops on potato yield and soilborne disease and their economic implications in potato production. *Am. J. Potato Res.* **2014**, *91*, 429–439. [CrossRef]
19. Larkin, R.P.; Honeycutt, C.W. Effects of different 3-year cropping systems on soil microbial communities and Rhizoctonia diseases of potato. *Phytopathology* **2006**, *96*, 68–79. [CrossRef]
20. Larkin, R.P.; Honeycutt, C.W.; Griffin, T.S.; Olanya, O.M.; Halloran, J.M.; He, Z. Effects of different potato cropping system approaches and water management on soilborne diseases and soil microbial communities. *Phytopathology* **2011**, *101*, 58–67. [CrossRef]
21. Larkin, R.P.; Honeycutt, C.W.; Griffin, T.S.; Olanya, O.M.; He, Z.; Halloran, J.M. Cumulative and residual effects of different potato cropping system management strategies on soilborne diseases and soil microbial communities over time. *Plant Pathol.* **2017**, *66*, 437–449. [CrossRef]
22. Olanya, O.M.; Honeycutt, C.W.; He, Z.; Larkin, R.P.; Halloran, J.M.; Frantz, J.M. Early and late blight potential on Russet Burbank potato as affected by microclimate, cropping systems, and irrigation management in Northeastern United States. In *Sustainable Potato Production: Global Case Studies*; He, Z., Larkin, R.P., Honeycutt, C.W., Eds.; Springer: Amsterdam, The Netherlands, 2012; pp. 43–60.
23. Olanya, O.M.; Larkin, R.P.; Halloran, J.M.; He, Z. Relationships of crop and soil management systems to meteorological variables and potato diseases on a Russet Burbank cultivar. *J. Agric. Meteorol.* **2014**, *70*, 91–104. [CrossRef]
24. Larkin, R.P. Cumulative and residual effects of potato cropping system management strategies on soil physical, chemical, and biological properties. *Phytopathology* **2015**, *105*, S4.
25. Larkin, R.P.; Griffin, T.S.; Honeycutt, C.W.; Olanya, O.M.; He, Z. Potato cropping system management strategy impacts soil physical, chemical, and biological properties over time. *Soil Tillage Res.* **2021**. submitted.

26. He, Z.; Honeycutt, C.W.; Griffin, T.S.; Larkin, R.P.; Olanya, O.M.; Halloran, J.M. Increases in phosphatase and urease activities in potato fields by cropping rotation practices. *J. Food Agric. Environ.* **2010**, *8*, 1112–1117. [CrossRef]
27. He, Z.; Honeycutt, C.W.; Olanya, O.M.; Larkin, R.P.; Halloran, J.M. Soil test phosphorus and microbial biomass phosphorus in potato fields. *J. Food Agric. Environ.* **2011**, *9*, 540–545. [CrossRef]
28. He, Z.; Honeycutt, C.W.; Olanya, O.M.; Larkin, R.P.; Halloran, J.M.; Frantz, J.M. Comparison of phosphorus status and organic matter composition in potato fields with different crop rotation systems. In *Sustainable Potato Production: Global Case Studies*; He, Z., Larkin, R.P., Honeycutt, C.W., Eds.; Springer: Amsterdam, The Netherlands, 2012; pp. 61–79.
29. Belanger, G.; Walsh, J.R.; Richards, J.E.; Milburn, P.H.; Ziadi, N. Yield response of two potato cultivars to supplemental irrigation and N fertilization in New Brunswick. *Am. J. Potato Res.* **2000**, *77*, 11–21. [CrossRef]
30. Honeycutt, C.W.; Clapham, W.M.; Leach, S.S. Crop rotation and N fertilization effects on growth, yield, and disease incidence in potato. *Am. Potato J.* **1996**, *73*, 45–61. [CrossRef]
31. Porter, G.A.; Sisson, J.A. Response of Russet Burbank and Shepody potatoes to nitrogen fertilizer in two cropping systems. *Am. Potato J.* **1991**, *68*, 428–463. [CrossRef]
32. Zaeen, A.A.; Sharma, L.K.; Jasim, A.; Bali, S.; Buzza, A.; Alyokhin, A. Yield and quality of three potato cultivars under series of nitrogen rates. *Agrosystems Geosci. Environ.* **2020**, *3*, e20062. [CrossRef]
33. Zebarth, B.J.; Bélanger, G.; Cambouris, A.N.; Ziadi, N. Nitrogen fertilization strategies in relation to potato tuber yield, quality, and crop N recovery. In *Sustainable Potato Production: Global Case Studies*; He, Z., Larkin, R.P., Honeycutt, C.W., Eds.; Springer: Amsterdam, The Netherlands, 2012; pp. 165–186.
34. Halloran, J.M.; Larkin, R.P.; DeFauw, S.L.; Olanya, O.M.; He, Z. Economic potential of compost amendment as an alternative to irrigation in Maine potato production systems. *Am. J. Plant Sci.* **2013**, *4*, 238–245. [CrossRef]
35. Griffin, T.S.; Porter, G.A. Altering soil carbon and nitrogen stocks in intensively tilled two-year rotations. *Biol. Fertil. Soils* **2004**, *39*, 366–374.
36. Porter, G.A.; Opena, G.B.; Bradbury, W.B.; McBurnie, J.C.; Sisson, J.A. Soil management and supplemental irrigation effects on potato: I. Soil properties, tuber yield, and quality. *Agron. J.* **1999**, *91*, 416–425. [CrossRef]
37. Wilson, C.; Zebarth, B.J.; Burton, D.L.; Goyer, C. Short-term effects of diverse compost products on soil quality in potato production. *Soil Sci. Soc. Am. J.* **2018**, *82*, 889–900. [CrossRef]
38. Wilson, C.; Zebarth, B.J.; Burton, D.L.; Goyer, C.; Moreau, G.; Dixon, T. Effect of diverse compost products on potato yield and nutrient availablity. *Am. J. Potato Res.* **2019**, *96*, 272–284. [CrossRef]
39. Abiven, S.; Menasseri, S.; Chenu, C. The effects of organic inputs over time on soil aggregate stability. *Soil Biol. Biochem.* **2008**, *41*, 1–12. [CrossRef]
40. Albaich, R.; Canet, R.; Pomares, F.; Ingelmo, F. Organic matter components and aggregate stability after application of different amendments to a horticultural soil. *Bioresour. Technol.* **2001**, *76*, 125–129. [CrossRef]
41. Diacono, M.; Montemurro, F. Long-term effects of organic amendments on soil fertility. A review. *Agron. Sustain. Dev.* **2010**, *30*, 401–422. [CrossRef]
42. He, Z.; Tazisong, I.A.; Senwo, Z.N.; Zhang, D. Soil properties and macro cations impacted by long-term applied poultry litter. *Commun. Soil Sci. Plant Anal.* **2008**, *39*, 858–872. [CrossRef]
43. Sexton, P.; Plant, A.; Johnson, S.B. Effect of a mustard green manure on potato yield and disease incidence in a rainfed environment. *Crop Manag.* **2007**. [CrossRef]
44. Sharifi, M.; Lynch, D.H.; Hammermeister, A.; Burton, D.L.; Messiga, A.J. Effect of green manure and supplemental fertility amendments on selected soil quality parameters in an organic potato rotation in Eastern Canada. *Nutr. Cycl. Agroecosyst.* **2014**, *100*, 135–146. [CrossRef]
45. Carter, M.R.; Holmstrom, D.; Sanderson, J.B.; Ivany, J.A.; DeHaan, R. Comparison of conservation with conventional tillage for potato production in Atlantic Canada: Crop productivity, soil physical proerties and weed control. *Can. J. Soil Sci.* **2005**, *85*, 453–461. [CrossRef]
46. Griffin, T.S.; Larkin, R.P.; Honeycutt, C.W. Delayed tillage and cover crop effects in potato systems. *Am. J. Potato Res.* ***2009***, 86, *79–87*. [CrossRef]
47. National Agricultural Statistics Service (NASS). New England Agricultural Statistics 2011. Available online: https://www.nass.usda.gov/Statistics_by_State/New_England_includes/Publications/Annual_Statistical_Bulletin/2011/fallpots2011.pdf (accessed on 20 August 2020).
48. Lulai, E.C.; Orr, P.H. Influence of specific gravity on yield and oil content of chips. *Am. Potato J.* **1977**, *56*, 379–389. [CrossRef]
49. Eldredge, E.P.; Holmes, Z.A.; Mosley, A.R.; Shock, C.C.; Stieber, T.D. Effects of transitory water stress on potato tuber stem-end reducing sugar and fry color. *Am. J. Potato Res.* **1996**, *73*, 517–530. [CrossRef]
50. Kincaid, D.C.; Westermann, D.T.; Trout, T.J. Irrigation and soil temperature effects on Russet Burbank quality. *Am. J. Potato Res.* **1993**, *70*, 711–723. [CrossRef]
51. Boyd, N.S.; Gordon, R.; Martin, R.C. Relationship between leaf area index and ground cover in potato under different management conditions. *Potato Res.* **2002**, *45*, 117–129. [CrossRef]

52. Xiong, D.; Chen, J.; Yu, T.; Gao, W.; Ling, X.; Li, Y.; Peng, S.; Huang, J. SPAD-based leaf nitrogen estimation is impacted by environmental factors and crop leaf characteristics. *Sci. Rep.* **2015**, *5*, 13389. [CrossRef]
53. Opena, G.B.; Porter, G.A. Soil management and supplemental nutrition effects on potato II. Root growth. *Agron. J.* **1999**, *91*, 426–431. [CrossRef]
54. He, Z.; Shankle, M.; Zhang, H.; Way, T. R.; Tewolde, H.; Uchimaya, M. Mineral composition of cottonseed is affected by fertilization management practices. *Agron. J.* **2013**, *105*, 341–350. [CrossRef]
55. Tewolde, H.; Adeli, A.; Sistani, K.R.; Rowe, D.E. Mineral nutrition of cotton fertilized with poultry litter or ammonium nitrate. *Agron. J.* **2011**, *103*, 1704–1711. [CrossRef]
56. Walworth, J.L.; Muniz, J.E. A compendium of tissue nutrient concentrations for field-grown potatoes. *Am. Potato J.* **1993**, *70*, 579–597. [CrossRef]
57. Warman, P.R.; Havard, K.A. Yield, vitamin and mineral contents of organically and conventionally grown potatoes and sweet corn. *Agric. Ecosys. Environ.* **1998**, *68*, 207–216. [CrossRef]
58. Magdoff, F.; Weil, R.R. *Soil Organic Matter in Sustainable Agriculture*; CRC Press: Boca Raton, FL, USA, 2004.
59. He, Z.; Zhang, M.; Zhao, A.; Olanya, O.M.; Larkin, R.P.; Honeycutt, C.W. Quantity and nature of water-extractable organic matter from sandy loam soils with potato cropping management. *Agric. Environ. Lett.* **2016**, *1*, 6. [CrossRef]