COVER CROPPING FOR CONTROL OF COLUMBIA ROOT KNOT NEMATODES

IN SHORT SEASON POTATO PRODUCTION

By

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COVER CROPPING FOR CONTROL OF COLUMBIA ROOT KNOT NEMATODES IN SHORT SEASON POTATO PRODUCTION

Abstract

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A study was conducted to identify cover crop options for controlling Columbia root knot nematodes in cool climates where potatoes are a mainstay of the crop rotation. The San Luis Valley of Colorado is offered here as a cool-climate test case location, focusing primarily on crops unfavorable to Columbia root knot nematode, a pest established in many potato growing regions of the United States. Sixty-three cultivars of Brassicas, cool-season grasses, warm-season grasses, legumes and summer annual forbs potentially adapted to growth in the San Luis Valley were tested for their capacity to host Columbia root knot nematode (Race 1), based on the cultivar's ability to increase, sustain, or diminish a known population of the pest. These tests were performed under controlled greenhouse conditions at a constant temperature of 21^{o}C. Reproductive factors were calculated based on these data, and cultivars ranked by host status as excellent, good, poor, or non-hosts to this pest. Accompanying potential benefits to the overall farming systems, through implementation of more diversified cover cropping rotations suppressive of Columbia root knot nematodes, include: use of more water-use efficient cultivars

and species in rotation; incorporation of legumes for fixation of nitrogen; stimulation of nutrient cycling and soil microbial community activity and diversity through increased root activity and root biomass additions. Information regarding root biomass development from each cultivar was gained in this study, and used as a co-factor in evaluating the potential of particular rotational crop cultivars to meet multiple management goals at one time, to grow crops that can both suppress Columbia root knot nematodes while increasing soil tilth. Brassica cultivars which look particularly promising for increased use are: radishes ‘Doublet’, ‘Terranova’, ‘Anaconda’, ‘Biofum Summer’, ‘Cassius’, and ‘Graza’; Ethiopian cabbage ‘Corrine’; Turnip x Kale hybrid ‘Winfred’. Legumes of non-host or poor host status, and with good root development are: Yellow Sweet Clovers ‘N-55’, ‘CZEC BDN 58-181’, ‘N-27’, ‘N-28’, ‘Yukon’, ‘Madrid’, ‘YBSC-TH Line’, ‘N-29’, ‘Erector’, and ‘Happy’; Alfalfa ‘Bullseye’. Warm-season grasses of great interest are: Sorghum-Sudangrass Hybrids ‘Sordan 79’, ‘Sweet Grazer Plus’, and ‘Xtra Graze’; Pearl Millets ‘TiffLeaf3’ and ‘Elite II’.

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Columbia Root Knot Nematode (CRKN) Development When Hosted In Potato Tubers

Infection symptoms from CRKN vary, from a translucent millimeter-diameter egg mass apparent only upon peeling the potato, to unsightly galling of the potato skin across the bulk of the potato skin surface area (David, 2007; Finley, 1981). The severity of infestation and of eventual damage is controlled primarily by the accumulated heat (4^{o}C to 25 ^{o}C) the CRKN experiences in the soil profile during the growing season, during which time female CRKN lay additional generations of progeny, multiplying eggs which hatch into tuber-infesting juveniles (David, 2007; Ferris et al., 1994; Griffin, 1985, O'Bannon and Santo, 1984). The greater the heat unit accumulation in the soil profile with a base temperature of 4^{o}C and a maximum temperature of 25 ^{o}C, the faster the time between egg laying, hatch, and reproductive maturity of the next generation of CRKN females (David, 2007; Pinkerton et al., 1991). Where growing conditions in which roots of a viable host are present for CRKN to feed upon, coupled with an accumulation of heat into the soil profile greater than 2,000 Growing Degree Days with 5 ^{o}C base temperature (GDD), an extremely small population of CRKN present at the start of the growing season can increase exponentially through successive egg laying-hatching-maturity cycles (Griffin, 1985; Pinkerton et al., 1991). When three or more generations of CRKN have formed and have infested tubers, populations of CRKN females are high enough to cause significant economic damage as their bodies swell, causing giant cell formation and bumps to develop on the tuber surface while discoloring the tuber flesh surrounding the incubating females (Ferris et al., 1994; Finley, 1981; Griffin, 1985; Pinkerton et al., 1991; Viaene et al., 2006). Nearly all of the CRKN infestation of tubers occurs within the top 5.25 mm between tuber skin and vascular ring (Viaene et al., 2006).

The 2,000 GDD soil temperature threshold (Griffin, 1985; Pinkerton et al., 1991) is normally exceeded in many of the major potato growing regions of the western USA (Griffin, 1985; Ingham, 2012; Riga, 2012), with a notable exception occurring often in the San Luis Valley of Colorado (Ingham, 2012; Pinkerton and McIntyre, 1987; Thompson, 2014a). Analysis of soil temperature data logger measurements kept by Thompson (2014a) demonstrated from years 2004-2014, across eleven monitoring sites in the San Luis Valley, only during one year, and only at one site, was in-field accumulation of GDD> 2,000. This corresponds to Thompson's (2014b) observation that galled potatoes from CRKN damage are a relatively uncommon defect experienced where start-of-growing-season CRKN populations (as described by soil sampling the preceding fall (Griffin, 1985)) are low.

Soil containing a resident population of CRKN has the capacity to develop juvenile females that will seek tuber flesh to burrow into, attempting to complete their life cycle and incubate eggs inside their bodies within the tubers. Provided the CRKN present in soil that eventually infect tubers are few (e.g. 1 per 250 cc soil (Ingham, 2012)) and are not exposed to > 2000 GDD, from the time of host introduction (e.g. potato planting) to the time of crop marketing, population growth can remain modest, and damage from gravid CRKN females present within the tuber will not have generated sufficient metabolites to cause enzymatic discoloration of tuber flesh, or to have accumulated the required heat units to incubate eggs sufficiently to gain in size and cause development of swollen masses resulting in a rough, galled tuber skin surface (Griffin, 1985).

Absence of galled tubers or dark masses beneath the skin surface does not assure tubers grown in soil with a resident population of CRKN are not infested with this pest (Griffin, 1985). Infestation can occur when juvenile females burrow through the skin and into the outer flesh of the tuber, but provided the populations of CRKN are very low and the heat unit accumulation in the presence of a viable host is < 2,000 GDD, risk of tuber damage of economic significance is low (Griffin, 1985; Pinkerton et al., 1991). Tubers with bumps on the skin and dark masses beneath the skin surface indicates that such tubers carrying CRKN females inside them, are harboring a latent infestation that is unlikely to experience fresh market sales rejections due to the inconspicuous nature of CRKN presence as translucent masses in the tuber tissue between skin and vascular ring (David, 2007; Ingham, 2012; Pinkerton et al., 1991). Should these same tubers be held in storage for multiple months at 3-5^{o}C and then utilized as seed potatoes, there is risk of introducing CRKN into a field not yet infested. Ferris et al. (1994) concluded that a high level of information is required to effectively manage in-field CRKN populations, which includes: 1) surveying the CRKN population level in-field the fall preceding potato planting; 2) assessing risk tolerance for damage to crop due to infestation from CRKN; and 3) quantifying the expected effects of rotation on CRKN populations, given these change greatly in response to a crop's ability to serve as a viable host to CRKN or not.

Management Strategies for Columbia Root Knot Nematode in Potato Production Systems: Breeding Potatoes Resistant to CRKN

Columbia root knot nematode populations have been found in each of the states in the western USA with commercial potato production (O'Bannon et al., 1982; Nyczepir et al 1982), including Colorado (David, 2007; Pinkerton and McIntyre, 1987). Once established, eradication of CRKN has not been effective (Riga, 2012). Resident populations off CRKN in agricultural fields have successfully been managed across the western USA for purposes of commercial potato production using integrated pest control measures that include chemical and biological approaches (Riga, 2012). Where short-season potato cultivars are grown, management of CRKN through primarily biological means is possible (Riga, 2011), due to the pest's reliance on accumulation of heat units sufficient for reproduction.

Resistance to CRKN Race 1 is documented in wild tuber-forming relatives to *Solanum tuberosum*, including ornamental nightshade (*Solanum bulbocastanum),* Fendlers's Horsenettle (*Solanum fendleri),* and *Solanum hougassi* (Brown et al., 1989, 1991 and 2004). Cultivars of potatoes (*Solanum tuberosum*) resistant to CRKN have not been identified through traditional breeding programs for commercial potato variety development, as of yet. Brown et al. (2009) developed breeding stock capable of resistance to *Melodogyne chitwoodi* attack, utilizing introgression to affect these crosses, but no commercially available cultivars have been developed bearing this resistance. Protoplast fusion has been used to transfer the CRKN-resistance traits from these wild-type *Solanum* species into *Solanum tuberosum* cv. Russet Burbank (Boydson et al., 2007). The protoplasm fusion technique is a topic of current debate within organic production regulatory bodies International Federation of Organic Agriculture Movements (IFOAM) and the United States Department of Agriculture National Organic Program (USDA-NOP) (Sutherland, 2014). Presently the USDA-NOP allows organic farmers to use seeds sourced through protoplasm fusion, while IFOAM deems protoplasm fusion as one method of genetic engineering and so not allowable within organic production. The protoplasm fusion technology for commercialization of CRKN-resistant potatoes to growers, and subsequently to the consuming public, has not yet become common but could be incorporated into parent stock for eventual cultivar development (Holm, 2015). The questions regarding genetic engineering, market access, and consumer acceptance of products which could carry a label of “genetically engineered” are ample, highlighting the need to focus on research of management strategies which could easily be adopted by certified organic and by non-organic farmers alike, including use of cover cropping for management of CRKN.

Synthetic Pesticide Use

Relatively few pesticides with nematicidal/nematistatic properties remain commercially available in the USA. Zasada et al. (2010) identified reasons for the phase-out of fumigant pesticides as tied to the economics of use, the environmental impact of fumigant use, and relating to human health concerns – nematicides are toxic and their use always carries some risk. Still, the potential for damage to potatoes is high if a resident population of CRKN is not managed in some way. The soil fumigants 1,3-dichloropropene (trade name = Telone II) and metam sodium (trade name = Vapam) are heavily regulated (Littke et al., 2012), with cost of use nearing US$400/acre (King and Taberna, 2013; Thompson, 2014b), where such an expense could constitute up to 20% of the cost of production for the entire crop year (Thompson, 2014b). The carbamate nematicide aldicarb (trade name = Temik) is no longer commercially available for use within potato cropping systems in the US due to concerns over its impact on the environment (Curran, 2010). The carbamate nematistat oxamyl (trade name = Vydate), registered for use during the growing season of the potato crop, is no longer commercially available. Manufacture of oxamyl ceased following a tragic accident in 2014 at DuPont’s La Porte, Texas manufacturing facility, in which a gas leak killed four and seriously injured one (Coons, 2016; Clarke, 2015; Trager, 2016; U.S. Chemical Safety and Hazard Investigation Board, 2015a and 2015b). Oxamyl had been a commonly used pesticide within the San Luis Valley of Colorado until 2015, when supply of this chemical was greatly limited following the closing of the manufacturing facility. Presently the synthetic insecticide spirotetramat (trade name = Movento) is registered for activity against nematodes in potatoes, however published data on its efficacy is limited.

Risk from both acute and chronic exposure to active ingredients such as the aforementioned is of growing concern among health professionals. Upon reviewing the state of children's health across the USA, the high rate of environmental pollution experienced by most children, accompanying health problems which result, and the risk of even low-dose pesticide residue exposure in children, the American Academy of Pediatrics (Roberts et al., 2012) advises pediatricians to counsel the families of patients to limit environmental exposure to toxins by opting for organic foods. Market demand for organic potatoes has driven increased organic potato production in Colorado (USDA-NASS, 2016) greatly over the past decade (Table 1), necessitating development of nematode management strategies that are not dependent upon use of synthetic nematicides/nematistats.

Biofumigant Crops in Rotation with Potatoes

Synthetic nematicides/nematistats are becoming less useful in potato cropping systems, and at the same time the study of biofumigant crops in controlling nematode populations has gained the interest of researchers globally. Particular species and cultivars of brassicas, Sudangrass, and Sorghum-Sudangrasses have attracted the most attention for their ability to generate and concentrate metabolites toxic to a variety of soil microbes, soilborne pathogens and pests. Species and cultivar selection, coupled with active management of these crop and soil environments, have proven essential to successfully diminishing plant parasitic nematode populations in soil (Fourie et al., 2016; Harrington, 1966; Joordens, 2015; Kruger et al., 2013;

Matthiessen and Kirkegaard, 2006; Mojtahedi et al., 1993a; Morra and Kirkegaard, 2002; Morra, 2004; Morra et al., undated; Riga, 2011, 2012; Santo et al., 1991). Crops containing chemical

Table 1. United States Department of Agriculture – National Agricultural Statistics Service data regarding conventional and organic potato production in the San Luis Valley, in Colorado and in the USA from 2008 – 2014.

Region	Category	2008	2014	% Change from 2008 to 2014	% of 2008 National Total	% of 2014 National Total
SLV	Potato, Total Acres	56,900	53,900	-5%	5%	5%
CO	Potato, Total Acres	61,300	59,800	-2%	6%	6%
USA	Potato, Total Acres	1,046,900	1,051,100	0%	---	---
CO	Potato, Organic Acres	1,921	3,523	83%	24%	29%
USA	Potato, Organic Acres	7,989	12,082	51%	---	---
CO	Potato Acres, Org / Total as %	3%	6%	---	---	---
USA	Potato Acres, Org / Total as %	1%	1%	---	---	---
CO	Potato, Total CWT	23,535,000	23,196,000	-1%	6%	5%
USA	Potato, Total CWT	415,055,000	442,170,000	7%	---	---
CO	Potato, Organic CWT	505,946	1,054,436	108%	22%	30%
USA	Potato, Organic CWT	2,274,406	3,558,664	56%	---	---
CO	Potato CWT, Org / Total as %	2%	5%	---	---	---
USA	Potato CWT, Org / Total as %	1%	1%	---	---	---
CO	Potato, Total Sales $	---	---	---	---	---
USA	Potato, Total Sales $	$ 3,494,193,000	$ 3,658,279,000	5%	---	---
CO	Potato, Organic Sales $	$ 6,084,090	$ 13,571,914	123%	20%	22%
USA	Potato, Organic Sales $	$ 30,023,572	$ 61,804,493	106%	---	---
USA	Potato Sales, Org/Total as %	1%	2%	---	---	---

Data Compiled from United States Department of Agriculture - National Agricultural Statistics Service (USDA-NASS) Quick Stats:
https://quickstats.nass.usda.gov/#59863644-D57C-3C98-AE7B-4F68618F8F0C
accessed 04 Jul 2016

compounds with known biocidal effect when incorporated into the soil as a green manure have been trialed extensively in potato rotations to study if and when nematodes can be controlled in this way (Fourie et al., 2016; Kruger, et al., 2013; Brown and Morra, 1997). Consistency of suppression of CRKN populations using biofumigant crops has increased as better methods for cultivar selection, management of crop growth, and methods of crop destruction and incorporation have improved (Matthiessen and Kirkegaard, 2006; Riga, 2012). Incorporation of flail mulched brassicas leaves and stems with high nematicidal glucosinolate content, establishing adequate moisture levels in soil immediately prior to green manuring, and timing incorporation of shredded residues into moist soil so as to minimize volatilization of active nematicidal compounds are each components critical for effective biofumigation against nematodes (Gimsing and Kirkegaard, 2006; Morra & Kirkegaard, 2002; Matthiessen and Kirkegaard, 2006). Riga (2011, 2012) validated the importance of an integrated approach to CRKN control, while stressing the significance of short-duration growing of CRKN hosts in achieving sufficient suppression of CRKN to allow potato production at low risk of CRKN infestation in the following growing season.

Host Status of Rotational Crops

Use of crops in rotation with potatoes where a resident CRKN population exists in-field, without knowing the potential for the cultivar selected to host CRKN, could lead to massive unintended increase in the pest inoculum (O'Bannon et al., 1982). Selection of rotational crop species and cultivars which are poor hosts or non-hosts to CRKN is of critical importance in the effort to actively manage resident populations of CRKN between potato crop cycles, to establish and maintain very low CRKN numbers prior to the potato crop cycle (Ferris et al., 1993, 1994). The extent to which individual crop cultivars support the completion of the CRKN life cycle is described through a calculation of the host's reproductive factor (Rf). A host's Rf value is determined by introducing a known number of CRKN eggs to a plant growth media free of nematodes and nematode eggs, along with the crop to be evaluated, measuring the population of CRKN eggs again upon completion of the crop cycle, and dividing the final egg density by the initial egg density, (i.e. Rf = Final Population CRKN Eggs / Initial Population CRKN Eggs) (Al-Rehiayani and Hafez, 1998; Cardwell and Ingham , 1997; Ferris et al., 1993; Griffin and Rumbaugh, 1996; Mojtahedi et al., 1989; 1991a; 1993a). The reproductive factor is a function of temperature (5^{o} C base soil temperature for CRKN), adequate time at or above the base temperature in the presence of growing roots to stimulate egg hatch, and the presence or absence of root and/or tuber tissues capable of serving as a food source for the nematodes to be able to complete their life cycle from hatching through to when new eggs are laid (David, 2007; Griffin, 1985). Wide variation in reproductive factors between cultivars within a crop species can occur (Ferris et al., 1993; Al-Rehiayani and Hafez, 1998; Mojtahedi et al., 1989, 1993a; Nycezpir et al., 1984), making selection of particular cultivars capable of achieving a very low reproductive factor (e.g. Rf < 1.0) in the effort to manage a resident CRKN population in-field.

Studies determining the CRKN host status for cultivars are varied, however many cultivars presently planted in the San Luis Valley of Colorado have not been described in literature, including numerous cultivars which are marketed nationally as biofumigants, and others which are marketed as same-species-proxies to cultivars of known Rf value (ignoring the aforementioned findings of cultivar difference within the same species). Selection of low-Rf value cultivars as either single-species crops or multi-species crop blends has the potential to reduce resident CRKN populations to levels manageable for potato production in mild, short-season environments, with low risk to the potato cash crop. Use of particular cultivars capable of biofumigant activity against CRKN, these same cultivars also possessing low-Rf values for CRKN, would give added potency to the efforts made at CRKN population suppression (Matthiessen and Kirkegaard, 2006). Beyond CRKN suppression, crop rotational benefits such as reduced water use (Merril et al., 2004), increased nutrient cycling and soil carbon deposition (McGuire, 2007) can be achieved with some of these same low-Rf value cultivars. The study which follows describes reproductive values relative to Columbia root knot nematode for 63 cultivars of different species which heretofore have not been described in literature.

INTRODUCTION

Columbia root-knot nematode (*Meloidogyne chitwoodi*, CRKN) is an established pest for many farmers in the western United States, including numerous farmers in the San Luis Valley of Colorado (David, 2007; Nyczepir et al., 1982; O'Bannon et al., 1982; Pinkerton and McIntyre, 1987). The potential for economic damage to potato crops from CRKN infection is substantial where pest populations are not managed actively (Finley, 1981; Griffin, 1985; Santo et al., 1991; Viglierchio, 1987). The consequences of infestation of potatoes with CRKN range from exclusion from premium markets with zero-tolerance standards, to the near total loss of marketable crops from physical tuber damage (Finley, 1981; Santo and O'Bannon, 1981, Santo et al., 1991).

Management of CRKN populations has been attempted utilizing synthetic fumigants applied to soil and synthetic antifeedants applied to crops (DuPont Crop Protection, 2013; David, 2007; Griffin, 1985; Riga, 2011; Santo et al., 1991); utilizing breeding efforts to make potato varieties that can resist CRKN infestation (Brown et al., 1989, 1991, 2004); utilizing bionematicide agents applied to soils intended to attack CRKN (Certis USA, 2016); and by utilizing non-host status and/or biofumigant status of rotational crops (Al-Rehiayani and Hafez, 1998; Ferris et al., 1993, 1994; Mojtahedi et al., 1989, 1993a). Economic, social and environmental costs of each approach are factors which influence the adoption of the aforementioned control measures, and the extent to which they are utilized. Due to the notably short growing season of the San Luis Valley from cold weather (frost free period on average from 10 June through 15 September), and the generally cool climate which exists in the region throughout the year (less than 2000 GDD based temperature 5^{o}C) (Pinkerton and McIntyre, 1987; Western Regional Climate Center, 2015), limited numbers of generations of CRKN develop within the span of a year (Ferris et al., 1994; Ingham, 2012; Pinkerton and McIntyre, 1987; Thompson, 2014a), creating opportunity to effectively manage low-level populations of CRKN with non-host and/or biofumigant plantings between potato crops (Ferris et al., 1994; Ingham, 2012; Riga, 2011, 2012).

In the San Luis Valley of Colorado, plantings of cover, green manure, hay and forage crops for use in potato rotations are increasingly diverse, including the use of multi-species seeding mixes. Desirable outcomes from adoption of novel rotational crops, instead of traditional commodity crops such as barley, wheat or alfalfa, include potential water savings over traditional rotational crops (Berton, 2006; Merrill et al., 2004; Thompson, 2005), increase of soil carbon deposition (McGuire, 2007), and improved pest management in preparation for the potato cropping year (Ferris et al., 1994).

Seeds of more than 50 different crop species are sold in the San Luis Valley, with a multitude available nationally (Reichenberger, 2013). Determining the host status (Al-Rehiayani and Hafez, 1998; Cardwell and Ingham, 1997; Ferris et al., 1993, 1994; Griffin, 1985; Griffin and Rumbaugh, 1996; Mojtahedi et al., 1989, 1991a, 1993a; Nycespir et al., 1984; O'Bannon et al., 1982; Santo et al., 1991) and potential for biofumigant activity (Gimsin and Kirkegaard, 2006; Harrington, 1966; Mathiessen and Kirkegaard, 2006; Mojtahedi et al., 1993b; Morra and Kirkegaard, 2002; Ploeg, 2008; Santo et al., 1991; Viaene and Abawi, 1998; Widmer and Abawi, 2002) of particular cultivars of crop species included in rotations with potatoes is critical for the proper management of crops to effect the continued suppression of CRKN, as multi-species seedings of crops become more common nationally, and particularly in the San Luis Valley. Little research information is available on the CRKN host status of crop cultivars of green manure, grains, hay and forage potentially useful as components of cover crops. Future planting and management decisions for improved soil tilth as an indicator of soil health, potato crop growth, and potato quality will be informed by the results of this research.

Research Goal and Objectives

The goal of this research was to identify best cover crop options for use in short season potato production, utilizing the San Luis Valley of Colorado as a test location.

Two specific objectives were to:

1. Evaluate rotational crops and cultivars available to San Luis Valley potato farmers for Columbia root knot nematode host status.
2. Describe potential benefits and/or limitations to implementation of alternate rotational crops and cultivars into the cropping system of the San Luis Valley.

MATERIALS AND METHODS

Crops and Cultivars

Crops and cultivars chosen for testing were determined from discussions with farmers and seed retailers and selected if they fit one or more of the following criteria: 1) presently widely planted in the San Luis Valley, but with little or no published data regarding CRKN-host status; 2) seed retailers active in cover crop sales in the San Luis Valley region advocating for particular crops and cultivars not before grown regionally and without data regarding CRKN-host status; and/or 3) crops and cultivars with a high degree of potential drought tolerance and with little supporting data regarding CRKN-host status. The Oregon State University Nematode Lab, under the direction of Russ Ingham, PhD, was contracted to perform the greenhouse evaluations through a series of five greenhouse studies, two performed in 2012, two in 2013, and one in 2014, performed to establish the host status of the cultivars examined (Table 2). Included among these 63 entries were eight (listed here as ‘AAAA’, ‘CCCC’, ‘DDDD’, ‘GGGG’, ‘HHHH’, ‘IIII’, ‘JJJJ’, and ‘KKKK’) whose evaluation as host of CRKN was funded by seed breeders and marketers, that were either numbered lines in development, but not available commercially at that time, or that were sponsored for research on the provision that the funder could choose whether or not to disclose the results. Results from these entries are included in this report to highlight variability across crop types and cultivars regarding CRKN host status. In the end, these anonymous entries have the utility of Variety-Not-Stated (vns) seed sources, which is a seed type of very limited use to those seeking to actively manage resident CRKN populations.

Greenhouse Study Design

The greenhouse evaluations employed by Cardwell & Ingham (1997) for testing the CRKN-host status of different popcorn cultivars were used as the template for the current study. Five separate greenhouse grow-outs were performed in batches (Table 2). Seeds of cultivars from each crop to be tested were planted in a greenhouse maintained at a constant 21^{o} C into seedling trays, using steam pasteurized soil mix to prevent unintended introduction of CRKN with soil comprised of two parts sand/one part loam. Supplemental lighting to maintain a 12 hour-day and 12 hour-night was used, and plants were fertilized with Osmocote (time release, 19-6-12) and Miracle-Gro (liquid, 24-8-16). When seedlings reached three-weeks-old, transplanting occurred. Transplanting consisted of three seedlings of the same cultivar being set into 3.785 L pots containing steam pasteurized potting mix of two parts sand/one part loam, and pots were then inoculated with 5,000 eggs of *M. chitwoodi*, race 1 obtained from greenhouse cultures maintained on ‘Stephens’ soft white winter wheat. Several days after transplanting,

Table 2. Crops and cultivars tested for CRKN host status.

Crop Type	Scientific Name	Common Name	Cultivar	Batch
Brassica	*Brassica carinata*	Ethiopian Cabbage	'Corrine'	1
	Brassica juncea	Indian Mustard	'Caliente 61'	1
	Brassica juncea	Indian Mustard	'Kodiak'	4
	Brassica juncea	Indian Mustard	'Pacific Gold'	1, 4
	Brassica napus	Kale x Turnip Hybrid	'Winfred'	1
	Eruca sativa	Arugula	'Nemat'	2
	Raphanus sativus	Fodder Radish	'Anaconda'	1
	Raphanus sativus	Fodder Radish	'Canavarro'	4
	Raphanus sativus	Fodder Radish	'Carwoodi'	4
	Raphanus sativus	Fodder Radish	'Cassius'	1
	Raphanus sativus	Fodder Radish	'Defender'	1
	Raphanus sativus	Fodder Radish	'Doublet'	1
	Raphanus sativus	Fodder Radish	'Graza'	2
	Raphanus sativus	Fodder Radish	'Image'	1
	Raphanus sativus	Fodder Radish	'Tajuna'	4
	Raphanus sativus	Fodder Radish	'Terranova'	1, 4
	Brassica carinata, Sinapis alba, Raphanus sativus	50% Ethiopian Cabbage + 40% White Mustard + 10% Fodder Radish	'Biofum Summer'	1
	R.sativus & E.sativa	70% Fodder Radish + 30% Arugula	'Trio'	1
Cool-Season Grass	*Avena sativa*	Common Oat	'Monida'	1
	Avena strigosa	Black Oat	'Soil Saver'	4
	Hordeum vulgare	Malting Barley	'Hockett'	4
	Lolium multiflorum	Annual Ryegrass	KKKK	1
	Secale cereale	Winter Cereal Rye	'Aroostook'	2
	Secale cereale	Winter Cereal Rye	'Elbon'	1
	Triticum aestivum L.	Hard White Spring Wheat	'IdaMax'	4
	Triticum aestivum ssp aestivum	Soft White Winter Wheat	'Stephens'	1, 2, 3, 4, 5
Warm-Season Grass	*Pennisetum glaucum*	Pearl Millet	'Elite II'	3
	Pennisetum glaucum	Pearl Millet	'TiffLeaf3'	3
	Pannicum miliaceum	Prosso Millet	'Dawn'	3
	Sorghum bicolor	Sorghum-Sudangrass	'Sordan 79'	3
	Sorghum bicolor	Sorghum-Sudangrass	'Sweet Grazer Plus'	3
	Sorghum bicolor	Sorghum-Sudangrass	'Xtra Graze'	3
	Sorghum bicolor	Sorghum-Sudangrass	AAAA	3
	Sorghum bicolor	Sorghum-Sudangrass	DDDD	3
	Sorghum bicolor	Sorghum-Sudangrass	GGGG	3
	Sorghum bicolor	Sorghum-Sudangrass	HHHH	3
	Sorghum bicolor	Sudangrass	CCCC	3
	Sorghum bicolor	Sudangrass	IIII	3
	Sorghum bicolor	Sudangrass	JJJJ	3
Summer Annual Forb	*Fagopyrum esculentum*	Buckwheat	'Mancan'	4
	Phacelia tanacetiflora	Phacelia	'Balo'	4
	---	---	'Lacewing & Ladybug'	2

Table 2 (continued). Crops and cultivars tested for CRKN host status.

Legume	*Lathyrus sativus L*	Chickling Vetch	'AC Greenfix'	1
	Pisum sativum	Forage Pea	'4010'	1
	Cicer arietinum	Garbanzo Bean	'Desi'	4
	Medicago sativa	Alfalfa	'Bullseye'	1
	Melilotus officianalis	Yellow Sweet Clover	'Yukon'	5
	Melilotus officianalis	Yellow Sweet Clover	'0001213'	5
	Melilotus officianalis	Yellow Sweet Clover	'CZEC BDN 58-181'	5
	Melilotus officianalis	Yellow Sweet Clover	'Erector'	5
	Melilotus officianalis	Yellow Sweet Clover	'Goldtop'	5
	Melilotus officianalis	Yellow Sweet Clover	'Happy'	5
	Melilotus officianalis	Yellow Sweet Clover	'Madrid'	5
	Melilotus officianalis	Yellow Sweet Clover	'N-27'	5
	Melilotus officianalis	Yellow Sweet Clover	'N-28'	5
	Melilotus officianalis	Yellow Sweet Clover	'N-29'	5
	Melilotus officianalis	Yellow Sweet Clover	'N-55'	5
	Melilotus officianalis	Yellow Sweet Clover	'Norgold'	5
	Melilotus officianalis	Yellow Sweet Clover	'TH Line'	5
	Onobrychis viciifolia	Sainfoin	'Shoshone'	4
	Vicia sativa	Cahaba Vetch	vns	4
	Vicia faba	Fava Bean	'Snow Bird'	4

thinning of plants to one strong plant per pot occurred. Cultivars evaluated were placed on a greenhouse bench in a randomized block design with five replications of each cultivar entry. Along with the cultivars for which Rf values had not previously been determined, the known excellent CRKN host plant, 'Stephens' soft white winter wheat, was included as a positive control to allow comparison of cultivars of a grow-out batch against a crop that normally should show a very high Rf, and to ensure that viable eggs were introduced, and that environmental conditions within pots and greenhouse were managed appropriately for the hatching and growth of CRKN.

Plants were grown in the presence of CRKN eggs for a length of time equivalent to the duration of a short-season hay or forage crop (89-101 days), which is ample time and GDD accumulation at the constant 21^{o} C of the greenhouse to ensure that CRKN reproduction would be observed if a particular plant was a host (Ingham, 2012; Pinkerton et al., 1991). At harvest, roots were gently washed free of soil, cut into 2- to 4-cm pieces and shaken for three minutes in 0.5% sodium hypochlorite (bleach) to degrade the sticky gelatinous matrix which surrounds CRKN eggs and allow eggs to detach from roots (Hussey and Barker, 1973). Soil surrounding roots tends not to contain significant numbers of CRKN eggs, relative to the roots themselves, based on previous validation work done in which soils and roots were extracted separately for CRKN eggs (Ingham, 2016). The bleach solution was poured through a 1 mm screen to collect the roots and onto a 25 µm screen to collect the eggs, which were rinsed into a counting dish and counted under a stereomicroscope. Washed roots were weighed to measure root mass per pot. The reproductive factor (Rf) was then calculated for each plant by dividing the number of eggs recovered at harvest (Pf) by the number of eggs in the inoculum (Pi = 5,000) (Oostenbrink, 1966).

Statistical Analyses

'Stephens' was included in all 5 greenhouse grow-outs because this cultivar is a known positive control for CRKN. 'Stephens' Rf values from all experiments were combined and an analysis of variance was performed with the statistical package R 'aov' function (R Foundation for Statistical Computing, Vienna, Austria). Batch was significant (P value = 0.05, so an adjusted reproductive factor (Rf_{adj}) from across greenhouse grow-outs was calculated using the mean Rf value of all 'Stephens' wheat entries. Each Rf value from all other crops was adjusted based on the relative value of 'Stephens' during the particular grow-out in which it was included. The assumption of homogeneity of variances for all Rf_{adj} was tested in R with the Fligner-Killeen test (function 'fligner test'). Variances were highly skewed and were not homogeneous after log or square root transformation. Rf_{adj} values were separated in R with the Kruskal-Wallis test (package ‘agricolae’, function ‘kruskal’: a non-parametric test applied where variances are not equal and multiple tests are compared simultaneously), using both the Bonferroni P adjustment, and the Students T Test. Bonferroni P adjustment, an especially conservative method, was applied to the independent tests so the overall confidence would be maintained across grow-out results, and data across greenhouse grow-outs could be evaluated together. A more liberal approach of separating means, the Students T Test, was employed for comparison within and between greenhouse grow-outs. Root biomass was also adjusted in the same fashion as done with Rf values and analyzed with the Kurskal-Wallis test with means separated by Bonferroni analysis and by Students T Test. These data also had heterogeneous variances and a significant batch effect ($P<0.001$). Ranked means for the non-parametric analysis results were calculated, to offer an alternate scale for visualizing the separation between lowest and highest Rf_{adj} values.

The crops, species and cultivars employed in the trials are identified in Table 2. Crops and cultivars selected based on expressed interest of interviewed potato farmers and seed salespeople active in the San Luis Valley, and reports of high biofumigant potential, high water use efficiency, high nutrient cycling potential, and high biomass production potential (Berton, 2006; Clapperton, 2011; Merrill, 2004; Office of Technology Assessment, 1983; Riga, 2012, Thompson, 2005).

RESULTS AND DISCUSSION

Columbia root knot nematode Host Status Discoveries

Results from the greenhouse studies to determine CRKN host status (Table 3) are displayed by crop type: brassica, cool-season grass, warm-season grass, legume, and summer annual forb – to facilitate within-type comparisons. Ferris et al., 1993 devised a categorical assessment of host status based on their experience and observations following a logarithmic pattern, where cultivars with CRKN Rf = 0.00 – 0.10 being assigned Non-Host status; Rf = 0.11-1.0 assigned Poor Host status; Rf = 1.01-10.0 assigned Good Host status, and Rf > 10.0 assigned Excellent Host status. Descriptors of host status as per the aforementioned categorical assessment accompany the Rf_{adj} values listed in Tables 3 and 5. As an aside, a fifth category, that of Maintenance Host was employed by Ferris et al., 1993 for those cultivars with Rf ~ 1.0, however the Rf range associated with a maintenance label was not furnished by the authors, and so the maintenance host category was not utilized in this present analysis.

The Rf_{adj} value for 'Stephens' soft white wheat (the positive control cultivar present in each of the grow-outs) was 32.49, qualifying as an Excellent Host. From the ranked means analysis, 'Stephens' was second only to 'Desi' Garbanzo in capacity to host CRKN and drive the organism to reproduce. Within each crop type, the cultivars evaluated ranged greatly in their Rf_{adj} values, with the exception of the cultivars in the warm-season grass category, which all proved to be of poor or non-host status. Cultivars exist from the warm-season grass group that do host CRKN (Al-Reyiayani and Hafez, 1998; Mojtahedi et al., 1993; Santo et al., 1991), however the selection of the cultivars included for testing here was rigorous, to screen for those cultivars likely to be non-hosts.

Table 3. Adjusted reproductive factors for CRKN host status for each of the cultivars evaluated, comparing separation of means by Bonferroni and Students T Test.

Crop Type	Crop & Cultivar	Reps	CRKN Host Rating*	Rf.adj Mean	Rf.adj SD	Rf.adj Min	Rf.adj Max	Rf.adj Ranked Means	Rf.adj Bonferroni	Rf.adj Students T Test
Brassica	Mustard Indian Kodiak	5	Excellent	15.17	9.54	6.17	29.29	294.1	abcde	abcd
Brassica	Mustard Pacific Gold	10	Good	5.89	5.77	0.65	18.77	262.9	abcdefghi	cdefgh
Brassica	Mustard Caliente 61	5	Good	1.93	1.84	0.73	5.07	238.2	abcdefghij	defghi
Brassica	Radish Oilseed Image	5	Good	1.25	1.10	0.09	2.60	221.9	abcdefghijkl	hijkl
Brassica	Radish Forage Graza	5	Poor	0.54	0.34	0.20	0.99	207.9	bcdefghijklm	ijklm
Brassica	Arugula Nemat	5	Poor	0.60	0.65	0.07	1.50	197.9	cdefghijklmn	ijklmno
Brassica	Turnip Hybrid Winfred	5	Poor	0.33	0.21	0.09	0.61	195.4	cdefghijklmn	ijklmno
Brassica	Radish Cassius	5	Poor	0.20	0.22	0.01	0.53	167.2	fghijklmnop	lmnopqrs
Brassica	Blend Biofum Summer	5	Poor	0.13	0.10	0.03	0.26	166.8	fghijklmnop	lmnopqrst
Brassica	Cabbage Ethiopian Corrine	5	Poor	0.12	0.13	0.02	0.32	155.3	ijklmnop	mnopqrstu
Brassica	Radish Oilseed Anaconda	5	Non-Host	0.05	0.05	0.00	0.11	118.6	jklmnop	rstuvwxyzA
Brassica	Arugula Trio	5	Non-Host	0.07	0.15	0.00	0.33	84.8	mnop	wxyzAB
Brassica	Radish Oilseed Defender	5	Non-Host	0.01	0.03	0.00	0.06	74.0	nop	yzAB
Brassica	Radish Fodder Cannavaro	5	Non-Host	0.00	0.01	0.00	0.02	69.7	op	zAB
Brassica	Radish Oilseed Terranova	10	Non-Host	0.00	0.01	0.00	0.04	64.1	p	B
Brassica	Radish Fodder Carwoodi	5	Non-Host	0.00	0.00	0.00	0.00	55.5	p	B
Brassica	Radish Fodder Tajuna	5	Non-Host	0.00	0.00	0.00	0.00	55.5	p	B
Brassica	Radish Oilseed Doublet	5	Non-Host	0.00	0.00	0.00	0.00	55.5	p	B
Cool-Season Grass	Oat Black Soil Saver	5	Excellent	42.58	19.21	19.70	66.81	327.2	ab	ab
Cool-Season Grass	Wheat Stevens	25	Excellent	32.49	20.15	5.48	93.36	315.9	ab	ab
Cool-Season Grass	Oat Forage Monida	5	Excellent	21.99	17.37	6.42	47.29	303.4	abc	abc
Cool-Season Grass	Rye Cereal Aroostook	5	Good	9.87	7.30	5.77	22.81	284.8	abcdef	abcde
Cool-Season Grass	Wheat HWS IdaMax	5	Excellent	14.94	17.02	1.40	42.72	282.9	abcdefg	abcdef
Cool-Season Grass	Rye Elbon	5	Good	4.91	3.53	1.96	10.69	265.4	abcdefghi	cdefgh
Cool-Season Grass	Barley Malt Hockett	5	Good	1.87	1.27	0.06	3.40	231.7	abcdefghijk	efghij
Cool-Season Grass	Ryegrass Annual KKKK	5	Poor	0.82	1.04	0.12	2.50	205.8	bcdefghijklm	ijklmn
Legume	Garbanzo Desi	5	Excellent	69.22	34.28	44.72	128.81	339.0	a	a
Legume	Vetch Chickling AC Greenfix	5	Excellent	17.17	10.21	4.93	30.22	297.8	abcd	abc
Legume	Fava Bean Snowbird	5	Good	9.64	6.13	1.68	15.74	280.4	abcdefgh	bcdefg
Legume	Pea Spring Forage 4010	5	Excellent	19.28	16.37	0.01	40.47	268.5	abcdefghi	cdefgh
Legume	Yellow Sweet Clover vns	5	---	1.39	1.67	0.39	4.35	226.4	abcdefghijk	fghijk
Legume	Sainfoin Shoshone	5	Good	3.34	6.23	0.10	14.46	224.4	abcdefghijkl	ghijk
Legume	Yellow Sweet Clover Goldtop	5	Good	2.76	5.30	0.01	12.20	191.0	cdefghijklmno	ijklmnop
Legume	Yellow Sweet Clover Norgold	5	Good	1.16	1.65	0.00	3.76	177.7	defghijklmno	jklmnopq
Legume	Yellow Sweet Clover 1213	5	Good	3.08	6.31	0.00	14.35	176.0	defghijklmno	jklmnopq
Legume	Yellow Sweet Clover Happy	5	Poor	0.11	0.14	0.03	0.35	157.4	hijklmnop	mnopqrstu
Legume	Yellow Sweet Clover Erector	5	Non-Host	0.07	0.06	0.01	0.15	150.8	ijklmnop	nopqrstuv
Legume	Yellow Sweet Clover N-29	5	Poor	0.43	0.81	0.00	1.88	141.0	jklmnop	opqrstuvw
Legume	Yellow Sweet Clover TH Line	5	Non-Host	0.07	0.06	0.00	0.13	137.2	jklmnop	pqrstuvwx
Legume	Yellow Sweet Clover Madrid	5	Non-Host	0.09	0.14	0.00	0.34	130.2	jklmnop	qrstuvwxy
Legume	Yellow Sweet Clover Yukon	5	Non-Host	0.09	0.12	0.00	0.28	124.8	jklmnop	qrstuvwxyz
Legume	Cahaba Vetch GCS vns **	5	---	0.22	0.45	0.00	1.03	123.4	jklmnop	qrstuvwxyzA
Legume	Alfalfa Bullseye	5	Non-Host	0.04	0.07	0.00	0.17	110.0	klmnop	tuvwxyzAB
Legume	Yellow Sweet Clover N-28	5	Poor	0.16	0.34	0.00	0.76	101.9	lmnop	uvwxyzAB
Legume	Yellow Sweet Clover N-27	5	Non-Host	0.03	0.05	0.00	0.12	97.7	mnop	vwxyzAB
Legume	Yellow Sweet Clover CZEC BDN 58-181	5	Non-Host	0.00	0.00	0.00	0.01	67.5	op	AB
Legume	Yellow Sweet Clover N-55	5	Non-Host	0.00	0.00	0.00	0.00	55.5	p	B
Summer Annual Forb	Lacewing & Ladybug Blend ***	5	---	7.07	4.49	2.01	14.30	274.8	abcdefghi	bcdefgh
Summer Annual Forb	Buckwheat Mancan	5	Poor	0.44	0.48	0.00	1.19	170.5	efghijklmnop	klmnopqr
Summer Annual Forb	Phacelia Balo	5	Non-Host	0.01	0.01	0.00	0.02	83.9	mnop	xyzAB
Warm-Season Grass	Sudangrass hybrid JJJJ	5	Poor	0.48	0.44	0.02	1.20	196.4	cdefghijklmn	ijklmno
Warm-Season Grass	Sorg-Sudan Xtra Graze	5	Poor	0.77	1.03	0.00	2.42	159.1	ghijklmnop	mnopqrst
Warm-Season Grass	Sorg-Sudan Sweet Grazer Plus	5	Poor	0.49	0.50	0.00	1.13	156.1	ijklmnop	mnopqrstu
Warm-Season Grass	Sorg-Sudan hybrid HHHH	5	Non-Host	0.08	0.09	0.00	0.23	138.3	jklmnop	pqrstuvwx
Warm-Season Grass	Sorg-Sudan hybrid GGGG	5	Non-Host	0.03	0.04	0.00	0.09	110.3	klmnop	stuvwxyzAB
Warm-Season Grass	Sorg-Sudan hybrid IIII	5	Poor	0.40	0.90	0.00	2.01	94.4	mnop	vwxyzAB
Warm-Season Grass	Millet Pearl Elite II	5	Non-Host	0.02	0.04	0.00	0.09	92.8	mnop	wxyzAB
Warm-Season Grass	Millet Pearl TiffLeaf3	5	Non-Host	0.01	0.03	0.00	0.07	75.9	nop	yzAB
Warm-Season Grass	Sorg-Sudan hybrid DDDD	5	Non-Host	0.01	0.03	0.00	0.07	75.9	nop	yzAB
Warm-Season Grass	Sudangrass hybrid CCCC	5	Non-Host	0.00	0.01	0.00	0.02	70.6	op	zAB
Warm-Season Grass	Sorg-Sudan hybrid AAAA	5	Non-Host	0.00	0.00	0.00	0.00	55.5	p	B
Warm-Season Grass	Sorg-Sudan hybrid Sordan 79	5	Non-Host	0.00	0.00	0.00	0.00	55.5	p	B
Warm-Season Grass	Millet Prosso Dawn **	5	---	0.00	0.00	0.00	0.00	55.5	p	B

* CRKN Host Rating adapted from Ferris et al., 1993 established a qualitative scale to describe host status based on Rf value in which Rf of 0-0.10 = Non-Host; 0.11-1.00 = Poor Host; 1.01-10.0 = Good Host; > 10.0 = Excellent Host.

** Replicates died prior to harvest - did not withstand greenhouse trial conditions, making data collected on these entries subject to question.

*** Multispecies blend not fully accounted for in actual species present in pots

Looking to the CRKN host rating and the Rf_{adj} data on Table 3 provides a starting point for evaluation of particular cultivars relative to risk of increasing populations of CRKN. In addition, review of the ranked means gives a second look at the relative rankings of all entries corresponding with their separation of means. In reviewing the Bonferroni separation of means, and the Students T Test separation of means for Rf_{adj} (Table 3), the conservative nature of the Bonferroni approach appears excessively restrictive to allow assignment of differences. Under the Bonferroni analysis cultivars shown to have very high Rf_{adj} values as Excellent Hosts are grouped with Good, Poor, and on occasion Non-Host status cultivars. An example of this phenomenon can be found by referring to Table 3, Rf_{adj} Bonferroni column, legume crop grouping, in which no significant difference is found between Garbanzo 'Desi' (Excellent Host) and Yellow Sweet Clover 'Erector' (Non-Host), despite qualifying as polar opposites in the Ferris et al. (1993) host categories, and having a difference in ranked means of 188.2, on a scale of 0 to 339.0 (Garbanzo 'Desi' Ranked Mean Score 339.0 (scale maximum) - Yellow Sweet Clover 'Erector' Ranked Mean Score 150.8 = difference of 188.2) . Utilizing the alternate separation of means scale provided with the Students T Test on Table 3 gives a much closer fit of Rf_{adj} data aligning with the Ferris et al. (1993) host status categorical assessment, allowing better definition of useful and not useful cultivars to plant for actively managing a CRKN population.

Adopting the Students T Test separation of means as the reference for further discussion in this paper does present the concern whether statistical differences demonstrated between cultivars will be accepted too easily. The consequence of incorrectly selecting a cultivar for use as a rotational crop preceding potatoes could be grave should a population of CRKN already be present in the field in question, and the crop grown is in fact a very effective host of the pest. In practice, most likely those who are seeking to actively manage a resident CRKN population would only be looking to those cultivars of Non-Host (Rf = 0.00 -0.10) or Poor Host (Rf 0.11 – 1.0) status relative to this pest, given its tremendous potential to increase in population within the span of one warm growing season. Using the Students T Test mean separation framework on Table 3, and reviewing the maximum Rf_{adj} values listed there, 17 of the 63 cultivars evaluated have ranges from minimum Rf_{adj} to maximum Rf_{adj} values which straddle the divide between Poor Host and Good Host status, as described by Ferris et al. (1993). Of these 17 cultivars, only 8 have low adjusted means which keep them in the Poor Host status category, leaving the remaining 9 which have high adjusted means, propelling them into the Good Host status category. The 8 entries with low adjusted means, but with replicates that yielded adjusted Rf values that individually qualified in the Good Host range (as they appear in Table 3) are: brassica Arugula 'Nemat'; cool-season grass Annual Ryegrass 'KKKK'; legume Yellow Sweet Clover 'N-29'; summer annual forb Buckwheat 'Mancan'; warm-season grass Sudangrass Hybrid 'JJJJ'; warm-season grass Sorghum-Sudangrass 'Xtra Graze'; warm-season grass Sorghum-Sudangrass 'Sweet Grazer Plus'; warm-season grass Sorghum-Sudangrass Hybrid 'IIII'. If in fact these cultivars are inconsistently Poor Hosts, and upon occasion serve as Good Hosts in the amount of CRKN reproduction they will support in the span of a growing season, a strategy to minimize risk from possible hosting would be to include as a majority of seeds per acre cultivars with known capacity to be non-hosts of CRKN and/or to have biofumigant potential against CRKN (should the rotational crop be destined for green manure). Examples of such cultivars with both non-host and biofumigant character may be found in Table 3 in the entries: brassica Radish Oilseed 'Terranova'; brassica Fodder 'Carwoodi'; brassica Radish

Fodder 'Tajuna'; brassica Oilseed 'Doublet'; warm-season grass Sorghum-Sudangrass Hybrid 'AAAA'; warm-season grass Sorghum-Sudangrass Hybrid 'Sordan 79'.

Utilization of crops bred specifically for their biofumigant potential, planted in fields with a resident CRKN population, requires careful management, to assure full suppressive potential of the CRKN population may occur by the end of the biofumigant crop cycle. Commercially available crops advertised as having biofumigant and "nematode-suppressive" characteristics are many, and included in this study for evaluation of CRKN host capacity were: Sorghum-Sudangrass Hybrid 'Sordan 79'; 'Kodiak' Indian Mustard; 'Pacific Gold' Indian Mustard; 'Caliente 61' Indian Mustard; 'Image' Oilseed Radish; 'Nemat' Arugula; 'Cassius' Radish; 'Biofum Summer Blend' Radish; 'Anaconda' Oilseed Radish; 'Trio' Arugula; 'Defender' Oilseed Radish; 'Cannavaro' Fodder Radish; 'Terranova' Oilseed Radish; 'Carwoodi' Fodder Radish; 'Tajuna' Fodder Radish; 'Doublet' Oilseed Radish; 'Soil Saver' Black Oats.

Sorghum-Sudangrass Hybrid 'Sordan 79' is a cultivar used extensively in the San Luis Valley, for its non-host status relative to CRKN and for its biofumigant potential (Mojtahedi et al., 1993), and was included in this study for comparative analysis, resulting in $Rf_{adj} = 0.00$ (Table 3). Biofumigant activity can be enhanced by chopping of stressed vegetative material and immediate incorporation of 'Sordan 79', due to elevated levels of prussic acid (hydrogen cyanide) in stressed tissues, which can increase biofumigation potential against CRKN when the material is incorporated into moist soil (Mojtahedi et al, 1993). Viane and Abawi (1998) concluded between six and eight weeks of sudangrass growth under optimal growing conditions would be needed to generate enough biomass to have a biofumigant effect upon incorporation of the crop. Other non-host cultivars of warm-season grasses identified in this study are Sorghum-

Sudan Hybrids ‘HHHH’ (Rf_{adj} = 0.08); ‘GGGG’ (Rf_{adj} = 0.03); ‘DDDD’ (Rf_{adj} = 0.01); ‘AAAA’ (Rf_{adj} = 0.00). Sudangrass Hybrid ‘CCCC’ (Rf_{adj} = 0.00), and Pearl Millet cultivars ‘Elite II’ (Rf_{adj} = 0.02) and ‘TiffLeaf3’ (Rf_{adj} = 0.01) fit non-host status, as well. Replicates of ‘Dawn’ Prosso Millet died prior to harvest of CRKN eggs and plant roots, making conclusions of host status difficult to determine. Plants of this variety grew very poorly under the greenhouse conditions used, creating uncertainty relative to the actual host status determination.

Several of the brassica crops chosen for evaluation were bred and marketed specifically for their high concentration of glucosinolates and capacity to reduce nematode populations upon incorporation through chopping and green manuring into moist soil. To accomplish this, these crops must generate massive amounts of aboveground growth to achieve concentrations of potentially nematicidal glucosinolates sufficient to have a successful biofumigant effect against CRKN. The focus of the present study is on the CRKN host status of these crops, to determine which cultivars can suppress CRKN populations as they grow. Potential suppression of CRKN further, upon incorporation of vegetative materials capable of biofumigation, would be an added benefit and has been described extensively by others (Fourie et al., 2016; Harrington, 1966; Joordens, 2015; Kruger et al., 2013; Matthiessen and Kirkegaard, 2006; Mojtahedi et al., 1993a; Morra and Kirkegaard, 2002; Morra, 2004; Morra et al., undated; Riga, 2011, 2012; Santo et al., 1991). The three Indian mustard cultivars ‘Kodiak’ (Rf_{adj} = 15.17), ‘Pacific Gold’ (Rf_{adj} = 5.89), and ‘Caliente 61’ (Rf_{adj} = 1.93) ranked as either good or excellent hosts for CRKN (Table 3). ‘Image’ Oilseed Radish proved a good host (Rf_{adj} = 1.25) for CRKN. ‘Cassius’ Radish (Rf_{adj} = 0.20) and ‘Biofum Summer Blend’ Radish (Rf_{adj} = 0.13) ranked as poor hosts for CRKN, as did ‘Nemat’ Arugula (Rf_{adj} = 0.60) (note: please refer to previous discussion point regarding Poor Host classification for Nemat Arugula and risk assessment relative to CRKN population increase). ‘Anaconda’ Oilseed Radish (Rf_{adj} = 0.05), ‘Trio’ Arugula (Rf_{adj} = 0.07), ‘Defender’ Oilseed Radish (Rf_{adj} = 0.01), ‘Canavaro’ Fodder Radish (Rf_{adj} = 0.00), ‘Terranova’ Oilseed Radish (Rf_{adj} = 0.00), ‘Carwoodi’ Fodder Radish (Rf_{adj} = 0.00), ‘Tajuna’ Fodder Radish (Rf_{adj} = 0.00), and ‘Doublet’ Oilseed Radish (Rf_{adj} = 0.00) all ranked as non-hosts for CRKN.

The significance of whether the crop is an excellent host for CRKN and a potent biofumigant comes in part from the inherent inefficiency of fumigation, whether it be biologically-based or synthetic, at reducing CRKN populations (Griffin, 1985; Riga, 2011, 2012). Mojtahedi et al. (1993b) found that brassica leaves shredded and incorporated into soil as a biofumigant were more effective at killing CRKN juvenilles (J2) than egg masses when incorporated into soil. Under optimal conditions, fumigation with the most potent synthetic fumigant currently available in conventional potato production systems, 1,3-dichloropropene (trade name = Telone II), is expected to be 90% at best, typically leaving a resident (though much-reduced) population of CRKN behind to regrow (Riga, 2011). Given the log-linear rate of growth CRKN commonly exhibits in the presence of a viable host (Ferris et al., 1994), planting of a good or excellent host to this pest would likely increase risk rather than diminish it relative to increasing CRKN resident population size and potato tuber damage. The biofumigant potential of particular cultivars rests in the ability to grow large amounts of the biocidal vegetative material to have effect upon incorporation via green manuring, which would require great investment in water, fertility, and management in that crop to assure maximum CRKN suppression. Where resources to optimize biomass and glucosinolate production are limited, utilizing crops that are non-hosts to CRKN becomes critical.

Though advertised broadly as capable of resolving nematode concerns, Black Oats (*Avena strigosa*) of the variety trialed here were not useful additions to potato rotations with

CRKN concerns. The cultivar ‘Soil Saver’ proved an excellent host (Rf_{adj} = 42.58) for CRKN (Table 3), and black oats are not known to have biocidal activity against CRKN when incorporated as a green manure. Research on plants of the species *Avena strigosa* has resulted in variable suppression of nematodes, depending upon cultivar and upon species of nematodes present (Dial, 2014), however the cultivar ‘Soil Saver’ proved an excellent host of CRKN, and would not be an option for use in potato rotations where CRKN is already established. Within the category of cool-season grasses, excellent CRKN hosts appeared in ‘Monida’ Forage Oats (Rf_{adj}=21.99) and in ‘IdaMax’ Hard White Spring Wheat (Rf_{adj}=14.94). Cereal rye cultivars ‘Aroostook’ (Rf_{adj}=9.87) and ‘Elbon’ (Rf_{adj}=4.91) ranked as good hosts to CRKN, as did the malt barley cultivar ‘Hockett’ (Rf_{adj}=1.87). Annual ryegrass ‘KKKK’ (Rf_{adj}=0.82) rated as a poor host, however experienced a broad spread in range of replicate data within the good host realm, requiring caution in employing this cultivar for aggressive management of a resident CRKN population.

A rotation crop which is a good host to CRKN can produce even higher populations than a potato crop. Pinkerton et al. (1991) estimates 1000 GDD from winter into warm season are needed to complete first generation when hosted by potatoes, given that roots must develop from potato seed piece before overwintering J2 can begin to mature, approximately. One thousand GDD are needed to effect a first hatch (resulting in second generation), while later generations need only 500-600 GDD. Based on Pinkerton et al. (1991), if dealing with a fast-growing good or excellent CRKN host plants with large root mass in early-season (e.g. early-spring seeded ‘Elbon’ cereal rye, Rf_{adj}=4.91), generation times are most likely closer to 500-600 GDD for first generation and for each successive generation, as compared to potatoes which have very slow root development from time of planting for the first several weeks to follow. The assumption here is that a good to excellent host would only need 500-600 GDD to go from J2 swimming in soil to viable egg-layers, from the start of spring, assuming roots are already present in early spring to be hosted.

Summer annual forb ‘Mancan’ Buckwheat rated as a poor host (Rf_{adj}=0.44), but with enough range in the replicate data to merit caution when using this cultivar, as well. A second summer annual forb tested for CRKN host status, ‘Balo’ Phacelia, proved a non-host (Rf_{adj}=0.01), and may be an interesting addition to mixes of crops in which pollinator and predatory insect habitat are goals, as this plant flowers profusely and is a great alternate nectar and pollen source for beneficial insects in general. A blend of flowers marketed as ‘Lacewing & Ladybug Mix’ was intended for evaluation; however complication in successfully planting each of the species in the mix in the replicated pot study made determination of the full mix’s CRKN host status not possible. Identifying cool-season tolerant crops with consistent CRKN-suppressive capacity remains an important area of study, noting how few have been described in literature (Widmer and Abawi, 2002).

Interest in legume inclusion in potato rotations, for the sake of biological nitrogen fixation for use in certified organic production, grows as demand for organic potatoes increases and input costs for certified organic nitrogen sources remain high. Results from inoculation of the legume crops and cultivars with CRKN Race 1 show low Rf_{adj} values (Table 3) in: ‘Bullseye’ Alfalfa (Rf_{adj}=0.01); Yellow Sweet Clover cultivars ‘Happy’ (c), ‘Erector’, ‘N-29’ (Rf_{adj}=0.07), ‘N-29’ (Rf_{adj}=0.43), ‘TH Line’ (Rf_{adj}=0.07), ‘Madrid’ (Rf_{adj}=0.09), ‘Yukon’ (Rf_{adj}=0.09), ‘N-28’ (Rf_{adj}=0.16), ‘N-27’ (Rf_{adj}=0.03), ‘Czec BDN 58-181’ (Rf_{adj}=0.00); and ‘N-55’ (Rf_{adj}=0.00). All other legume entries evaluated proved to have either good or excellent host status for CRKN. All replicates of Cahaba Vetch vns. died prior to the conclusion of the grow-outs, making any findings regarding host status inconclusive. 'Bullseye' Alfalfa was marketed as resistant to both Races 1 and 2 of *M. chitwoodi*. Unfortunately, the alfalfa cultivar evaluated was discontinued by the seed company soon after this research was completed, and no cultivars of the yellow sweet clovers evaluated are commercially available in North America at present. Seeds for most of the yellow sweet clover entries in this study originated from public seed banks in the USA and Canada, however the seed available at commercial scale is solely "Variety-Not-Specified" (vns). There is wide variation in the Rf_{adj} values found in this study between yellow sweet clover accessions, with individual replicates ranging in Rf_{adj} values from 0.00 to 14.35. It is not possible to rely upon yellow sweet clover, in the form of seed variety-not-specified, to consistently provide a desirably-low reproductive factor for CRKN. Opportunities for seed increase of those varieties that show promise relative to CRKN host status abound, provided the seed's identity can be maintained via varietal certification and verification upon commercialization. Host studies were performed utilizing *M. chitwoodi* race 1 (the race which alfalfa does not host), however races 1 and 2 are both present in the San Luis Valley (Ingham, 2012). Though yellow sweet clover is a not-too-distant relation of alfalfa, no research reports regarding its host status of race 2 could be found. Perhaps this remains yet one more area of inquiry to explore in the search for rotational crops and cultivars that will provide optimal benefits to following potato crops.

Incorporation of Root Growth Characteristics Into Rotation Crop Decision-Making

The process of selecting rotational crops to optimize subsequent potato production is an inherently complex analysis which must take into consideration economic aspects including cost of production, land tenure, and opportunity costs of utilizing non-cash crop plantings within a rotation. Opportunity costs can come also where potato planting is anticipated, but must be forgone for a year or more in the absence of effective fumigation, due to dangerously high CRKN establishing prior to the intended potato cycle. Further, agronomic factors including potential for nutrient cycling, nitrogen fixation, weed control options, and - where resident CRKN populations exist - host status of the crops to be utilized and the weed populations to be managed. The selection criteria utilized for each circumstance could be different; however if one of the primary concerns of the field in question is cost and efficacy of CRKN management, then host status must be a major determining factor in rotation crop selection. A second factor worth considering is the potential impact different crops may have on the soil microbiome, via root activity. Rooting extent and root biomass regulate the rate at which water and nutrient uptake can occur, and the potential for root exudates to impact the soil foodweb.

In the course of this study, root mass measurements in the presence of CRKN were recorded for each of the cultivars tested (Table 4). This simplistic but useful measure allows for comparisons of rooting among the five greenhouse grow-outs performed through the ranking of means, here scaled from 14.5 ('IdaMax' Wheat, 0.9 g roots/pot) to 317.5 (Sudangrass Hybrid 'JJJJ', 66.0 g roots/pot). Separation of means by Students T Test and Bonferroni analysis show large differences in root mass development, including significant differences within the same species as in the case of both radishes (root mass means ranging from 4.6 g/pot to 24.7 g/pot) and yellow sweet clovers (root mass means ranging from 18.8 g/pot to 57.8 g/pot).

Extreme cost and economic risk are outcomes when CRKN populations are ineffectively managed. Under the cool climate environment, high priority should be given to the selection of rotational crops to precede potato plantings that are non- or poor hosts of CRKN to avoid these risks. Additionally, further gains towards improved nutrient cycling, nitrogen fixation, and water use efficiency may be had by evaluating both CRKN host status and root mass development together (Table 5), with low CRKN host status being the primary factor, and high root mass development being a secondary consideration.

Host status for CRKN and root mass can be viewed in the same instance in Table 5, here arranged by crop type, by adjusted Rf (highest to lowest), and includes data for root mass in accompaniment. Excluding those cultivars of good or excellent host status from consideration, and selecting for cultivars in the upper 3-quartiles for mean root mass (mean root mass > 12.1 g/pot), provides a streamlined view of cultivars that may be especially interesting to trial at field-scale (Table 6). The upper 3-quartiles are selected here instead of some more rigorous trimmed data set to allow those cultivars with high biofumigant capability, but modest root growth, to continue on a short-list of cultivars worth trialing, for the paired purpose of suppressing CRKN and building tilth through increased root growth.

Santo et al. (1991) surmised that growth of a brassica crop would be optimal for affecting CRKN suppression if the crop were terminated within two months of seeding under summer growing conditions. If green manuring a crop that hosts CRKN, suppression of the pest would be most effective if the crop terminated before further CRKN egg additions to the soil could occur (Santo et al, 1991). Such short duration growth is desirable, as it requires less water to achieve the suppressive effect than a full-season crop. However, due to the cool climate of the San Luis Valley and its brief frost-free period (generally June 10 – Sep 15), utilization of any of the above-listed or already-described poor or non-host cover crops allows limited opportunity for growth of both a CRKN-suppressive crop and a cash crop during the same calendar year. Maximizing the utility gained from the CRKN-suppressive planting becomes critical where cropping windows are especially short. Growth of non-host or poor host cultivars such as those listed in Table 6, if even for short duration, has the potential of significantly reducing resident

Table 4. Root mass by end of grow-out for each of the 63 cultivars inoculated with CRKN eggs, comparing separation of means by Bonferroni and Students T Test.

Crop Type	Crop & Cultivar	Reps	Root Mass Mean, g/pot	Root Mass SD	Root Mass Min, g/pot	Root Mass Max, g/pot	Root Mass Ranked Means	Root Mass Bonferroni	Root Mass Students T Test
Brassica	Turnip Hybrid Winfred	5	25.9	10.1	13.3	39.5	174.6	defghijklm	klmnopq
Brassica	Blend Biofum Summer	5	25.4	6.7	17.7	32.4	174.4	defghijklm	klmnopq
Brassica	Radish Forage Graza	5	24.7	8.6	16.5	36.4	167.4	efghijklmn	lmnopqrs
Brassica	Cabbage Ethiopian Corrine	5	23.2	4.6	17.2	29.5	162.5	fghijklmno	mnopqrs
Brassica	Radish Oilseed Image	5	21.6	4.0	17.5	26.0	152.3	ghijklmnop	nopqrs
Brassica	Radish Oilseed Doublet	5	21.6	5.5	15.0	28.0	149.7	ghijklmnopq	nopqrs
Brassica	Radish Cassius	5	18.4	5.0	12.3	26.0	129.9	ijklmnopqr	pqrst
Brassica	Radish Oilseed Anaconda	5	16.4	2.0	13.3	18.7	115.2	klmnopqrst	stuv
Brassica	Radish Oilseed Terranova	10	13.8	6.1	3.6	22.7	100.4	lmnopqrst	tuvw
Brassica	Arugula Nemat	5	14.0	2.3	10.6	16.5	97.7	lmnopqrst	tuvwx
Brassica	Mustard Caliente 61	5	12.1	6.1	3.9	17.9	89.6	lmnopqrst	tuvwxy
Brassica	Radish Oilseed Defender	5	11.4	2.9	8.6	16.2	82.9	lmnopqrst	tuvwxyz
Brassica	Mustard Pacific Gold	10	10.1	8.5	1.9	26.3	76.6	mnopqrst	uvwxyz
Brassica	Arugula Trio	5	9.8	6.5	0.4	17.7	73.2	mnopqrst	uvwxyzA
Brassica	Radish Fodder Cannavaro	5	6.8	2.0	5.3	10.1	57.7	nopqrst	wxyzABCD
Brassica	Radish Fodder Carwoodi	5	5.7	2.1	3.2	8.2	51.5	opqrst	xyzABCD
Brassica	Radish Fodder Tajuna	5	4.6	2.0	1.7	6.6	44.2	pqrst	yzABCD
Brassica	Mustard Indian Kodiak	5	3.5	0.8	2.3	4.6	36.8	qrst	zABCD
Cool-Season Grass	Wheat Stevens	25	82.2	57.2	13.9	196.7	282.1	abcd	abcde
Cool-Season Grass	Rye Cereal Aroostook	5	46.9	6.7	36.4	54.6	272.4	abcdef	abcdef
Cool-Season Grass	Rye Elbon	5	41.1	11.2	30.6	57.7	250.1	abcdefg	bcdefgh
Cool-Season Grass	Ryegrass Annual KKKK	5	40.4	10.8	29.1	57.6	248.4	abcdefg	cdefgh
Cool-Season Grass	Oat Forage Monida	5	36.7	6.4	32.8	48.0	234.9	abcdefghij	efghij
Cool-Season Grass	Oat Black Soil Saver	5	8.3	3.3	3.2	12.3	65.1	mnopqrst	vwxyzAB
Cool-Season Grass	Barley Malt Hockett-MVC	5	6.7	3.2	2.2	10.5	56.2	nopqrst	wxyzABCD
Cool-Season Grass	Wheat HWS IdaMax	5	0.9	0.8	0.4	2.2	14.5	st	BCD
Legume	Yellow Sweet Clover Goldtop	5	57.8	16.6	43.8	86.1	296.3	abc	abcd
Legume	Yellow Sweet Clover N-55	5	54.6	9.8	42.0	65.9	296.0	abc	abcd
Legume	Yellow Sweet Clover YBSC-TH line	5	50.9	19.0	30.1	72.1	274.2	abcdef	abcdef
Legume	Yellow Sweet Clover 1213	5	46.2	6.5	36.5	52.8	271.6	abcdef	abcdef
Legume	Yellow Sweet Clover Madrid	5	45.3	10.5	34.2	59.7	267.9	abcdef	abcdefg
Legume	Yellow Sweet Clover Norgold	5	36.1	10.9	21.5	47.0	226.6	abcdefghijk	fghijk
Legume	Yellow Sweet Clover N-28	5	32.7	6.7	24.4	41.2	215.5	abcdefghijk	ghijkl
Legume	Garbanzo Desi	5	32.4	11.6	22.4	51.6	209.9	abcdefghijk	hijklm
Legume	Alfalfa Bullseye	5	31.8	10.8	20.8	45.7	206.1	abcdefghijk	hijklm
Legume	Yellow Sweet Clover Yukon	5	28.6	4.1	22.9	33.1	195.2	bcdefghijkl	ijklmn
Legume	Yellow Sweet Clover N-29	5	27.1	7.5	17.3	37.7	184.9	cdefghijkl	jklmno
Legume	Yellow Sweet Clover Erector	5	26.2	10.0	18.0	42.6	177.3	defghijkl	klmnop
Legume	Yellow Sweet Clover vns	5	25.7	5.5	19.1	32.0	177.1	defghijkl	klmnop
Legume	Vetch Chickling AC Greenfix	5	25.0	7.9	14.7	36.7	170.6	efghijklmn	lmnopqr
Legume	Yellow Sweet Clover CZEC BDN 58-181	5	23.5	3.8	18.8	28.5	164.0	fghijklmno	lmnopqrs
Legume	Yellow Sweet Clover N-27	5	24.5	11.8	13.3	39.1	162.7	fghijklmno	mnopqrs
Legume	Yellow Sweet Clover Happy	5	18.8	9.2	9.0	32.5	132.5	hijklmnopqr	opqrst
Legume	Sainfoin Shoshone	5	17.4	4.1	12.0	23.5	123.2	jklmnopqrs	qrst
Legume	Fava Bean Snowbird	5	13.5	7.0	3.0	21.8	96.5	lmnopqrst	tuvwxy
Legume	Pea Spring Forage 4010	5	7.2	3.5	4.1	12.8	59.6	nopqrst	wxyzABC
Legume	Cahaba Vetch GCS vns *	5	0.5	0.3	0.1	0.9	11.1	st	CD
Summer Annual Forb	Lacewing **	5	38.9	11.9	22.6	51.2	238.5	abcdefghi	efghi
Summer Annual Forb	Buckwheat Mancan	5	2.4	1.2	0.7	3.8	28.0	rst	ABCD
Summer Annual Forb	Phacelia Balo	5	0.7	0.4	0.2	1.2	14.6	st	BCD
Warm-Season Grass	Sudangrass hybrid JJJJ	5	66.0	11.7	51.2	83.3	317.5	a	a
Warm-Season Grass	Sorg-Sudan hybrid IIII	5	62.7	18.8	41.4	81.3	303.0	ab	a
Warm-Season Grass	Sorg-Sudan hybrid AAAA	5	57.8	12.5	40.3	74.0	302.4	ab	ab
Warm-Season Grass	Sorg-Sudan hybrid DDDD	5	54.5	4.3	49.4	60.4	298.0	abc	abc
Warm-Season Grass	Sorg-Sudan hybrid Sordan 79	5	51.8	12.9	29.1	60.8	285.7	abcd	abcde
Warm-Season Grass	Sorg-Sudan hybrid HHHH	5	48.1	9.1	37.8	58.5	279.0	abcde	abcdef
Warm-Season Grass	Sorg-Sudan hybrid GGGG	5	49.0	13.0	28.5	63.7	275.3	abcdef	abcdef
Warm-Season Grass	Sudangrass hybrid CCCC	5	41.9	12.1	27.6	54.6	250.1	abcdefg	bcdefgh
Warm-Season Grass	Sorg-Sudan Sweet Grazer Plus	5	41.2	15.2	26.5	65.3	244.9	abcdefgh	defghi
Warm-Season Grass	Sorg-Sudan Xtra Graze	5	38.0	4.8	33.3	46.0	241.1	abcdefghi	efghi
Warm-Season Grass	Millet Pearl TiffLeaf3	5	21.8	7.1	15.1	32.2	150.1	ghijklmnopq	nopqrs
Warm-Season Grass	Millet Pearl Elite II	5	16.8	11.4	7.6	35.6	118.4	klmnopqrst	rstu
Warm-Season Grass	Millet Prosso Dawn *	5	0.3	0.3	0.1	0.7	6.2	t	D

* Replicates died prior to harvest - did not withstand greenhouse trial conditions, making data collected on these entries subject to question.

** Multispecies blend not fully accounted for in actual species present in pots

Table 5. Combined CRKN host status and root mass data for the 63 cultivars evaluated with separation of means by Students T Test.

Crop Type	Crop & Cultivar	Replicates	CRKN Host Rating*	Rf.adj Mean	Rf.adj Students T Test	Root Mass Mean, g/pot	Root Mass Students T Test
Brassica	Mustard Indian Kodiak	5	Excellent	15.17	abcd	3.5	zABCD
Brassica	Mustard Pacific Gold	10	Good	5.89	cdefgh	10.1	uvwxyz
Brassica	Mustard Caliente 61	5	Good	1.93	defghi	12.1	tuvwxy
Brassica	Radish Oilseed Image	5	Good	1.25	hijkl	21.6	nopqrs
Brassica	Radish Forage Graza	5	Poor	0.54	ijklm	24.7	lmnopqrs
Brassica	Arugula Nemat	5	Poor	0.60	ijklmno	14.0	tuvwx
Brassica	Turnip Hybrid Winfred	5	Poor	0.33	ijklmno	25.9	klmnopq
Brassica	Radish Cassius	5	Poor	0.20	lmnopqrs	18.4	pqrst
Brassica	Blend Biofum Summer	5	Poor	0.13	lmnopqrst	25.4	klmnopq
Brassica	Cabbage Ethiopian Corrine	5	Poor	0.12	mnopqrstu	23.2	mnopqrs
Brassica	Radish Oilseed Anaconda	5	Non-Host	0.05	rstuvwxyzA	16.4	stuv
Brassica	Arugula Trio	5	Non-Host	0.07	wxyzAB	9.8	uvwxyzA
Brassica	Radish Oilseed Defender	5	Non-Host	0.01	yzAB	11.4	tuvwxyz
Brassica	Radish Fodder Cannavaro	5	Non-Host	0.00	zAB	6.8	wxyzABCD
Brassica	Radish Oilseed Terranova	10	Non-Host	0.00	B	13.8	tuvw
Brassica	Radish Fodder Carwoodi	5	Non-Host	0.00	B	5.7	xyzABCD
Brassica	Radish Fodder Tajuna	5	Non-Host	0.00	B	4.6	yzABCD
Brassica	Radish Oilseed Doublet	5	Non-Host	0.00	B	21.6	nopqrs
Cool-Season Grass	Oat Black Soil Saver	5	Excellent	42.58	ab	8.3	vwxyzAB
Cool-Season Grass	Wheat Stevens	25	Excellent	32.49	ab	82.2	abcde
Cool-Season Grass	Oat Forage Monida	5	Excellent	21.99	abc	36.7	efghij
Cool-Season Grass	Rye Cereal Aroostook	5	Good	9.87	abcde	46.9	abcdef
Cool-Season Grass	Wheat HWS IdaMax	5	Excellent	14.94	abcdef	0.9	BCD
Cool-Season Grass	Rye Elbon	5	Good	4.91	cdefgh	41.1	bcdefgh
Cool-Season Grass	Barley Malt Hockett-MVC	5	Good	1.87	efghij	6.7	wxyzABCD
Cool-Season Grass	Ryegrass Annual KKKK	5	Poor	0.82	ijklmn	40.4	cdefgh
Legume	Garbanzo Desi	5	Excellent	69.22	a	32.4	hijklm
Legume	Vetch Chickling AC Greenfix	5	Excellent	17.17	abc	25.0	lmnopqr
Legume	Fava Bean Snowbird	5	Good	9.64	bcdefg	13.5	tuvwxy
Legume	Pea Spring Forage 4010	5	Excellent	19.28	cdefgh	7.2	wxyzABC
Legume	Yellow Sweet Clover vns	5	---	1.39	fghijk	25.7	klmnop
Legume	Sainfoin Shoshone	5	Good	3.34	ghijk	17.4	qrst
Legume	Yellow Sweet Clover Goldtop	5	Good	2.76	ijklmnop	57.8	abcd
Legume	Yellow Sweet Clover Norgold	5	Good	1.16	jklmnopq	36.1	fghijk
Legume	Yellow Sweet Clover 1213	5	Good	3.08	jklmnopq	46.2	abcdef
Legume	Yellow Sweet Clover Happy	5	Poor	0.11	mnopqrstu	18.8	opqrst
Legume	Yellow Sweet Clover Erector	5	Non-Host	0.07	nopqrstuv	26.2	klmnop
Legume	Yellow Sweet Clover N-29	5	Poor	0.43	opqrstuvw	27.1	jklmno
Legume	Yellow Sweet Clover YBSC-TH line	5	Non-Host	0.07	pqrstuvwx	50.9	abcdef
Legume	Yellow Sweet Clover Madrid	5	Non-Host	0.09	qrstuvwxy	45.3	abcdefg
Legume	Yellow Sweet Clover Yukon	5	Non-Host	0.09	qrstuvwxyz	28.6	ijklmn
Legume	Cahaba Vetch vns **	5	---	0.22	qrstuvwxyzA	11.1	CD
Legume	Alfalfa Bullseye	5	Non-Host	0.04	tuvwxyzAB	31.8	hijklm
Legume	Yellow Sweet Clover N-28	5	Poor	0.16	uvwxyzAB	32.7	ghijkl
Legume	Yellow Sweet Clover N-27	5	Non-Host	0.03	vwxyzAB	24.5	mnopqrs
Legume	Yellow Sweet Clover CZEC BDN 58-181	5	Non-Host	0.00	AB	23.5	lmnopqrs
Legume	Yellow Sweet Clover N-55	5	Non-Host	0.00	B	54.6	abcd
Summer Annual Forb	Lacewing & Ladybug Blend ***	5	---	7.07	bcdefgh	38.9	efghi
Summer Annual Forb	Buckwheat Mancan	5	Poor	0.44	klmnopqr	2.4	ABCD
Summer Annual Forb	Phacelia Balo	5	Non-Host	0.01	xyzAB	0.7	BCD
Warm-Season Grass	Sudangrass hybrid JJJJ	5	Poor	0.48	ijklmno	66.0	a
Warm-Season Grass	Sorg-Sudan Xtra Graze	5	Poor	0.77	mnopqrst	38.0	efghi
Warm-Season Grass	Sorg-Sudan Sweet Grazer Plus	5	Poor	0.49	mnopqrstu	41.2	defghi
Warm-Season Grass	Sorg-Sudan hybrid HHHH	5	Non-Host	0.08	pqrstuvwx	48.1	abcdef
Warm-Season Grass	Sorg-Sudan hybrid GGGG	5	Non-Host	0.03	stuvwxyzAB	49.0	abcdef
Warm-Season Grass	Sorg-Sudan hybrid IIII	5	Poor	0.40	vwxyzAB	62.7	a
Warm-Season Grass	Millet Pearl Elite II	5	Non-Host	0.02	wxyzAB	16.8	rstu
Warm-Season Grass	Millet Pearl TiffLeaf3	5	Non-Host	0.01	yzAB	21.8	nopqrs
Warm-Season Grass	Sorg-Sudan hybrid DDDD	5	Non-Host	0.01	yzAB	54.5	abc
Warm-Season Grass	Sudangrass hybrid CCCC	5	Non-Host	0.00	zAB	41.9	bcdefgh
Warm-Season Grass	Sorg-Sudan hybrid AAAA	5	Non-Host	0.00	B	57.8	ab
Warm-Season Grass	Sorg-Sudan hybrid Sordan 79	5	Non-Host	0.00	B	51.8	abcde
Warm-Season Grass	Millet Prosso Dawn **	5	---	0.00	B	0.3	D

* CRKN Host Rating adapted from Ferris et al., 1993 established a qualitative scale to describe host status based on Rf value in which Rf of 0-0.10 = Non-Host; 0.11-1.00 = Poor Host; 1.01-10.0 = Good Host; > 10.0 = Excellent Host.

** Replicates died prior to harvest - did not withstand greenhouse trial conditions, making data collected on these entries subject to question.

*** Multispecies blend not fully accounted for in actual species present in pots

Table 6: Non-host and poor host status cultivars from the top 3 quartiles for mean root mass.

Crop Type	Crop & Cultivar	CRKN Host Rating*	Rf.adj Mean	Rf.adj Students T Test	Root Mass Mean, g/pot	Root Mass Students T Test
Brassica	Radish Oilseed Doublet	Non-Host	0.00	B	21.6	nopqrs
Brassica	Radish Oilseed Terranova	Non-Host	0.00	B	13.8	tuvw
Brassica	Radish Oilseed Anaconda	Non-Host	0.05	rstuvwxyzA	16.4	stuv
Brassica	Cabbage Ethiopian Corrine	Poor	0.12	mnopqrstu	23.2	mnopqrs
Brassica	Blend Biofum Summer	Poor	0.13	lmnopqrst	25.4	klmnopq
Brassica	Radish Cassius	Poor	0.20	lmnopqrs	18.4	pqrst
Brassica	Turnip Hybrid Winfred	Poor	0.33	ijklmno	25.9	klmnopq
Brassica	Arugula Nemat	Poor	0.60	ijklmno	14.0	tuvwx
Brassica	Radish Forage Graza	Poor	0.54	ijklm	24.7	lmnopqrs
Cool-Season Grass	Ryegrass Annual KKKK	Poor	0.82	ijklmn	40.4	cdefgh
Legume	Yellow Sweet Clover N-55	Non-Host	0.00	B	54.6	abcd
Legume	Yellow Sweet Clover CZEC BDN 58-181	Non-Host	0.00	AB	23.5	lmnopqrs
Legume	Yellow Sweet Clover N-27	Non-Host	0.03	vwxyzAB	24.5	mnopqrs
Legume	Yellow Sweet Clover N-28	Poor	0.16	uvwxyzAB	32.7	ghijkl
Legume	Alfalfa Bullseye	Non-Host	0.04	tuvwxyzAB	31.8	hijklm
Legume	Yellow Sweet Clover Yukon	Non-Host	0.09	qrstuvwxyz	28.6	ijklmn
Legume	Yellow Sweet Clover Madrid	Non-Host	0.09	qrstuvwxy	45.3	abcdefg
Legume	Yellow Sweet Clover YBSC-TH line	Non-Host	0.07	pqrstuvwx	50.9	abcdef
Legume	Yellow Sweet Clover N-29	Poor	0.43	opqrstuvw	27.1	jklmno
Legume	Yellow Sweet Clover Erector	Non-Host	0.07	nopqrstuv	26.2	klmnop
Legume	Yellow Sweet Clover Happy	Poor	0.11	mnopqrstu	18.8	opqrst
Warm-Season Grass	Sorg-Sudan hybrid AAAA	Non-Host	0.00	B	57.8	ab
Warm-Season Grass	Sorg-Sudan hybrid Sordan 79	Non-Host	0.00	B	51.8	abcde
Warm-Season Grass	Sudangrass hybrid CCCC	Non-Host	0.00	zAB	41.9	bcdefgh
Warm-Season Grass	Sorg-Sudan hybrid DDDD	Non-Host	0.01	yzAB	54.5	abc
Warm-Season Grass	Millet Pearl TiffLeaf3	Non-Host	0.01	yzAB	21.8	nopqrs
Warm-Season Grass	Millet Pearl Elite II	Non-Host	0.02	wxyzAB	16.8	rstu
Warm-Season Grass	Sorg-Sudan hybrid IIII	Poor	0.40	vwxyzAB	62.7	a
Warm-Season Grass	Sorg-Sudan hybrid GGGG	Non-Host	0.03	stuvwxyzAB	49.0	abcdef
Warm-Season Grass	Sorg-Sudan hybrid HHHH	Non-Host	0.08	pqrstuvwx	48.1	abcdef
Warm-Season Grass	Sorg-Sudan Sweet Grazer Plus	Poor	0.49	mnopqrstu	41.2	defghi
Warm-Season Grass	Sorg-Sudan Xtra Graze	Poor	0.77	mnopqrst	38.0	efghi
Warm-Season Grass	Sudangrass hybrid JJJJ	Poor	0.48	ijklmno	66.0	a

* CRKN Host Rating adapted from Ferris et al., 1993 established a qualitative scale to describe host status based on Rf value in which Rf of 0-0.10 = Non-Host; 0.11-1.00 = Poor Host; 1.01-10.0 = Good Host; > 10.0 = Excellent Host.

CRKN populations while intensifying root activity, accelerating nutrient capture and cycling in the process (McGuire and Johnson, 2009; Riga, 2011, 2012). The greenhouse grow-outs ranged from 89-101 days to assure sufficient heat unit accumulation to allow those plants which are hosts to CRKN to complete at least one generation during the trial period (Pinkerton et al., 1991; Ingham, 2012). Alternately, growing non-host or poor host crops capable of generating a large amount of biomass (both aboveground and belowground) is a mechanism to diminish CRKN numbers while encouraging development of improved soil tilth.

Utilizing short-duration plantings intended primarily to attract sedentary endoparasitic nematodes, such as CRKN, into the roots early in the life cycles of both plant and pest, can be managed to effectively trap these nematodes and prevent them from reproducing (Riga, 2012; Zasada et al., 2010). This method is highly sensitive to timing of mechanical crop destruction, to assure the CRKN have hatched and infested roots, but not developed sufficiently to begin depositing eggs into the soil environment. Assuring a short-duration crop cycle is critical by killing plant roots completely, prior to egg development by the infesting juvenile females (Zasada et al., 2010). Nemat Arugula, one of the cultivars evaluated in this study, was bred with an amazing capacity to attract nematodes to its roots as a result of the massive allocation of carbon in the form of root growth, and principally in the form of root exudates, that this plant delivers into the rhizosphere (Riga, 2012). 'Nemat' Arugula (Table 3) had notable variation in its replicates' CRKN reproductive factors, some falling into the good host range, suggesting similar variability could occur within a larger population of 'Nemat' Arugula seed. Use of 'Nemat' Arugula as a biofumigant trap crop grown for a very short period may be best, instead of as a component in a mix that is intended to be suppressive of CRKN but grown for an extended period (e.g. > 45 days). As with any biologically-based pest control approach, it is the adaptive ability of the practitioner when presented with new information that will allow success to be had in this realm.

CONCLUSIONS

In cool climates where potatoes are grown and Columbia root knot nematode is endemic, fumigant alternatives are essential for production of potato crops with limited economic tuber damage. The San Luis Valley of Colorado possesses a cool summer growing season, allowing active management of the CRKN population using the host status of rotational crops. Making use of information regarding a field's resident CRKN population levels, about the potential rotational crop's cultivar-specific CRKN Reproductive Factor (Rf), and regarding the growth potential for a particular crop and cultivar, allow for improved integrated management decisions to limit CRKN populations, and to reduce the risk of exceeding market thresholds for damaged tubers. Brassica cultivars which look particularly promising for increased use are: radishes 'Doublet', 'Terranova', 'Anaconda', 'Biofum Summer', 'Cassius', and 'Graza'; Ethiopian cabbage 'Corrine'; Turnip x Kale hybrid 'Winfred'. Legumes of non-host or poor host status, and with good root development are: Yellow Sweet Clovers 'N-55', 'CZEC BDN 58-181', 'N-27', 'N-28', 'Yukon', 'Madrid', 'YBSC-TH Line', 'N-29', 'Erector', and 'Happy'; Alfalfa 'Bullseye'. Warm-season grasses of great interest are: Sorghum-Sudangrass Hybrids 'Sordan 79', 'Sweet Grazer Plus', and 'Xtra Graze'; Pearl Millets 'TiffLeaf3' and 'Elite II'.

This study adds data on numerous cultivars previously not described in literature, relative to their status as CRKN hosts, and root growth potential under cool-climate growing conditions. Use of this information to inform rotational cropping selection, either as monoculture seedings or as polyculture mixes, should help producers diminish the economic and environmental risks they face when engaging fields in which CRKN reside and potatoes are part of the crop rotation.

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Addendum I: **Fertility Management and Food Value: Comparing Organic and Conventional Potato Production Systems - A Literature Review**

In reviewing early literature on the topic of organic and conventional potato (*Solanum tuberosum*) production, and the resulting yields, nutritional analyses, and soil fertility characteristics of the systems included in the studies, it becomes clear that many different approaches were taken to ask the same questions. And in this regard, conclusions based on sometimes-mismatched study areas and treatments were conflicting regarding the effects of organic and conventional fertility management on the nutritive value of food produced. The following literature review was conducted to address the question: "Are there nutritional differences between organic potatoes and conventional potatoes?"

***Overview of Known Nutritive Value of Potatoes* (*Solanum tuberosum*)**

White et al. (2009) provide a concise summary of the macro-nutrients, vitamins and minerals for which potatoes are best known, including carbohydrates, Cu, K, P, Fe, Zn, Mg, Mn, ascorbate, and to a lesser extent Se, I, and Ca. The authors note the generally low levels of nutrient absorption blockers such as phytate and oxalate, and the relatively high level of nutrient absorption facilitators such as ascorbate (vitamin C), which allow many of the minerals in potatoes to be easily assimilated into our bodies upon consumption. Though not essential nutrients, important to note is secondary plant metabolite development in potato plants and tubers, as these bioactive compounds have potential as antioxidants, as toxins, and/or as enzyme co-factors (Brandt & Molgaard, 2001; Benbrook et al, 2008). Brandt & Molgaard (2001) indicate most populations in developed countries do not experience chronic deficiencies of vitamins, minerals, proteins or carbohydrates, as diverse food sources consumed over a short period of time would likely cover most, if not all, essential nutrients. Still, it is the case that the greater the daily intake of vegetables and fruits, the smaller the risk of major deadly diseases in Western society, including cancer, cardiovascular disease and diabetes (Brandt & Molgaard, 2001). In this situation, the added health benefits of high vegetable and fruit consumption may come more from increased antioxidant intake than from simply increasing vitamin, mineral and energy consumption in Western societies (Brandt & Molgaard, 2001).

The production of secondary plant metabolites is in response to environmental x genetic interactions, with increased specific metabolite production in response to physiological triggers such as herbivory, drought stress, nitrogen limitation, and other similar stress events. Development of specific antioxidant secondary metabolites, such as chlorogenic acid (found in most potato types), lutein (one of the principal antioxidants present in carotenoid pigment of yellow-fleshed potatoes), and zeaxanthin (also a carotenoid pigment) is specific to certain potato genotypes (Brown, 2005). Brandt & Molgaard (2001) note that environmental conditions (including those influenced by crop management practices) can have systemic effect on the levels of secondary metabolites formed in the plant. Potatoes vary in their ability to develop mineral nutrition, and to form secondary metabolites, again due to the interaction between genetic potential and environment.

Yields of potatoes have risen greatly over the past 50 years, with some growing regions experiencing greater than two-fold increases in potatoes yields over that time period. Many crops have experienced similar rapid increases in production with the advent of potentially high yielding cultivars, the relative low-cost of soluble, high-analysis fertilizers such as ammonium sulfate, urea, and ammonium nitrate, and the implementation of intensive irrigation. Tremendous increases in crop yields have caused concern regarding a potential "dilution effect" (Jarrell and Beverly, 1981; Halweil, 2007; Davis, 2009), in which the plant is induced to set heavily, but remains physiologically and/or morphologically limited in its ability to establish balanced and adequate nutrition. Such limitation could inhibit normal, healthful produce development, and corresponding formation of desired secondary metabolites to add to the nutrient density of the food produced.

The extent to which tuber nutrient content can be influenced by supplemental nutrient additions to the soil and/or the plant is varied, with N, P, K, Mg and Ca additions showing positive correlations with elemental composition of tubers (White et al., 2009). In addition, negative interactions can occur, including: N additions corresponding with decreased Fe and P in tubers; P fertilization corresponding with decreased Mn in tubers; K addition to soil corresponding to decreased Ca and P in tubers; Ca fertilization corresponding to decreased Mg in tubers (White et al., 2009). These results suggest fertility inputs can negatively or positively affect the mineral nutritive content of potato.

Warman and Havard (1997) determined organically-grown tubers did contain more P, Mg, Na and Mn than tubers from conventionally-grown tubers. Woese et al. (1997) did not find consistent mineral nutrient differences between tubers from organic and conventional systems. Wszelaki et al. (2005) related findings that tuber skin and tuber flesh contained concentrations of K, Mg, P, S, and Cu significantly higher in organic fertility treatments (legume-containing crop rotation +/- composted dairy manure addition) as compared to the synthetic fertilizer-treated potatoes of the same variety, planted within the same field. Here, the authors identified differences between the taste of potatoes grown under organic conditions and those grown under conventional management, with the organic treatment showing greater intensity of glycoalkaloid compounds, components in flavor formation (and potential toxins, if excessive) within the potato. Differences in taste were not consistently found in the study by Woese, et al. (1997). Wszelaki et al. (2005) were forthcoming in identifying experimental design limitations of their own – they had different planting and harvest dates for the organic, as compared to the conventional potatoes, creating uncertainty whether the foods analyzed from each system were truly comparable. Nutrient accumulation and secondary metabolite formation are influenced by physiological age. An example of this is vitamin C (ascorbic acid), which appears to develop early in the growing season and is then partitioned through the tuber as the potato gains mass (Brown, 2010). Tubers which are harvested when small and physiologically young would tend to contain a higher concentration of vitamin C than would larger, older tubers. Having said this, Wszelaki et al. (2005) did not indicate in their methods that vitamin C was measured in their comparison. Magkos et al. (2003) did indicate, in their review of literature available, a tendency towards increased vitamin C levels in organic potatoes as compared to conventional ones. In an earlier study, Brandt and Molgaard (2001) indicated a tendency for organic produce to be low in vitamin C, based on the literature they reviewed, and theorized low vitamin C to be a result of limited nitrogen availability, an explanation contrary to Lee & Kader's (2000) description of high rates of N fertilizer causing decreases in vitamin C content of many fruits and vegetables, and is contrary to Brown's vitamin C x physiological sink size interaction theory (cited above). Brandt and Mogaard's observation that accumulation of vitamin C increases when the plant is subjected to oxidative stress – which could include such factors as full sunlight, drought, low nitrogen availability, herbicide damage – does not indicate how nitrogen metabolism interacts to affect vitamin C formation under organic or conventional production. Warman and Havard

(1998) reported no difference in tuber vitamin C or tuber yield comparing data from organic and conventional plots.

Organic farming systems tend to be nitrate- and ammonium-limited systems, but are often high in immobilized organic (carbon-bonded) forms of nitrogen, requiring mineralization to allow eventual uptake by the crop. Nitrogen availability to the growing potato plant is a critical component in determining vegetative mass, and in deciding overall progeny number per plant and tuber size potential. Possible interactions of organic or conventional fertility management in determining vitamin C content of tubers likely is linked to nitrogen availability, but more study may need to be done to establish the mechanism involved. In conventional potato cropping, highly soluble forms of N are frequently applied as the plant grows and as its demand for proteins increases. Within organic systems, potato plants are likely to experience the same progression of protein demand, but availability of nitrogen to match plant growth potential is likely to be limited, due to the more gradual release of N associated with microbial digestion of organic-N forms, resulting in generally smaller plant size, fewer tubers set, and smaller tubers at the finish of the growing season. Exceptions to this trend do occur, most often when organic nitrogen sources are heavily supplemented, or when the maturity of the organic system is such that mineralization is rapid and on-going. Woese et al., (1997) reviewed twenty-two scientific publications on organic and conventional potato nutrient content comparisons, reporting the majority of citations related either no difference or significantly higher vitamin C content in organically fertilized potatoes. In this same report, the authors could not distinguish clear trends for tuber nitrate, mineral content, or for flavor preference among the many studies reviewed. Halweil (2007) identified a tendency for plants fertilized heavily with large quantities of highly soluble nitrogen forms (e.g. urea, anhydrous ammonia, ammonium sulfate) to experience quick cell expansion but moderate to low uptake of micronutrients during the cell expansion period. Uptake of calcium and metal micronutrients (e.g. Cu) during cell expansion and cell wall formation is critical to ensuring well-functioning, strong cells capable of withstanding environmental and biotic stresses. Halweil's observation of rapid cell expansion from heavy N application correlating with reduced metal micronutrient uptake will likely remain a focus of researchers performing organic and conventional comparisons for years to come. Several of the literature reviews comparing organic and conventional foods, including potatoes, report conflicting evidence regarding mineral nutrient content in tubers (Brandt & Molgaard, 2001; Magkos et al, 2003; Hoefkens et al., 2009).

The potential for variability in mineral nutrients, and especially in the formation of specific organic acids, secondary metabolites, and reducing sugars does have a great genetic x environment interaction. Rodriguez Galdon et al. (2010) identify the utility in screening potato cultivars for specific organic acids and reducing sugars, as reducing sugars levels vary with interactions of climate, soil conditions, temperature, and cultivar grown, since reducing sugars, upon frying, can produce potentially carcinogenic acrylimides. While having identified the significant genetic x environment interaction, this report offered no insight into the organic vs. conventional fertility management to affect the environment. Faller & Fialho (2009) found polyphenols in organic produce were less stable after cooking, noting polyphenols present in conventionally grown vegetables as more stable, concluding there would be no antioxidant benefit to consumer health if subject organic produce is consumed after cooked. Unfortunately, Faller & Fialho did not offer a possible explanation of why organic produce would have less stable polyphenol antioxidants following cooking.

Though of great importance for consumer confidence, safety and health, the issue of pesticide residues in foods is not a primary focus of this report, though it is possible some pesticides could influence crop physiology adequately to regulate nutrient and secondary plant metabolite formation and allocation.

Farming System Maturity Effects on Harvested Food Quality

The length of time and sequence of crops to precede organic potatoes is another factor in the story of soil fertility, plant health, and subsequent nutritive value of the potato as a food. Nelson et al (2009) described the changes in soil health with increasing time between successive potato crops, noting increased total soil carbon and earthworm activity with longer spans between potato crops. Nelson et al. did not assess the nutrient composition of the potatoes grown in this study, but soil carbon building has been directly linked with a soil's capacity to supply mineral micronutrients to the plant, and consequently to the food produced from the carbon-enriched soil (Jones, 2010). Organic potato farmers tend to shy away from short intervals between potato crops on the same ground, since it typically takes longer periods of green manure crops, compost additions, and non-solanaceous crop growth to allow the soil to recover its fertility and relative microbial balance, to support the next healthy potato crop. The addition of composts, of more stable C sources into the system, and the encouragement of mycorrhiza fungi, all add to the C-sequestration capacity of the soil system. Within conventional potato systems, the time gap between potato crops is typically short-circuited with synthetic fertilizers and pesticides, with relatively few stable carbon inputs in the interim. In viewing literature on whether organic and conventional potatoes are nutritionally distinct, it seems there is still very little information regarding the role of stable carbon in the development of human-available nutrients within the potato. The findings of Reganold et al. (2009) of increased antioxidant capacity from strawberries and Mitchell et al. (2007) regarding tomatoes grown in more "mature" organic systems, as compared to the matched-pair conventionally produced strawberries and tomatoes fertilized with a synthetic or synthetic+organic (compost) fertility inputs respectively, gives rise to the question of the impact an organic system's "maturity" has on crop growth and on quality of foods produced therein. Crinnion's (2010) review of literature highlights that the longer the soil has been managed using organic production methods, the greater the nutritional difference in foods produced, when compared with foods produced within conventionally grown situations.

Challenges of Comparative Studies to Qualify Nutrient Density Differences

The question of whether organic food is distinct from conventional food has been asked since the time "organic" and "conventional" farming systems first were distinguished into unique categories. That question has been asked in myriad ways, and continues to be asked regularly by food consumers, included among them scientists eager enough to engage the topic. Potential components wondered about, regarding differences between organic and conventional foods, include pesticide residue levels, energy balance between systems, cost of food purchase, real cost of production accounting for the holistic system impact of food produced, and whether an organic food could provide nourishment distinct from a conventional food (Crinnion, 2010; Hajslova et al., 2005; Brandt & Molgaard, 2001; Lee & Kader, 2000; Woese et al., 2007). But the approach taken to answer the question of distinction is equally important as the posing of the question itself. In delving into peer-reviewed literature on the very topic of nutritional differences between organic and conventional produce, one discovers a multitude of ways researchers have attempted to determine differences. Some relied upon market survey sampling at the point of sale (consumer exposure survey), others compared crops by species, still others compared crops of the same type and cultivar, but planted and harvested at different times (Benbrook et al., 2008; Wszelaki, A., 2005). It seems how the question is asked of whether a potato, or a strawberry, or a kernel of wheat is more nutritive if it's grown organically as compared to conventionally is equally as important as whether the question is asked at all. Matched pair analysis (Benbrook et al., 2008; Reganold et al., 2010) is a developing tool researchers may employ to better screen existing literature, and to instruct the design of experiments which are inherently highly sensitive to environmental influence. Reganold et al. (2010) described a unique systematic evaluation process comparing existing side-by-side organic and conventional strawberry production, discovering organic strawberry production systems produced fruit with longer shelf-life, greater dry matter, higher antioxidant activity, higher concentration of ascorbic acid and phenolic compounds and lower concentration of P and K in fruit. Further findings from that study included organic-managed soils contained more total C and N, greater microbial biomass and activity, higher concentration of micronutrients; organic farmed soils contained greater numbers of endemic genes and greater functional gene abundance and diversity, including increased capacity for nitrogen fixation and pesticide degradation (Reganold et al., 2010). The findings of this study are cited here because the approach used does allow for direct comparison of the final product, with the possibility of future study to distinguish causal relationships regarding distinctions in food quality between systems.

Potato nutrient and secondary metabolite comparisons are many, but in a recent meta-analysis of data published between 1994 and 2008 on the topic of nutrient and contaminant contents between organic and conventional vegetables and potatoes, Hoefkens et al. (2009) concluded:

> "Only a limited number of studies comparing the nutrient and/or contaminant concentration of organic and conventional vegetables are available ("paired studies"). Additionally, the majority of the studies are of moderate or poor quality. The implication is that more of those paired studies are heavily needed."

From the data available, Hoefkens et al. observed inconsistent potato nitrate and vitamin C responses to organic fertility and system management. A distinction made by the authors regarding organic production is that "organic" is a process claim, not a product claim. The organic process is varied, depending on farm, region, crop and market, but falls into distinguishable categories based on general tenets of pesticide use, soil conservation and fertility input sourcing. "Conventional" is a term which is non-descript, defining only that the system is not certified as being "organic", casting a darker shadow when trying to understand conflicting nutritional results from what, on the surface, appear to be similar scenarios where organic and conventional systems are compared.

Summary

Interest in food produced organically and using more ecologically-sound food production practices continues to rise globally. With each day new information is publicized to describe health-promoting secondary plant metabolites found to be concentrated in particular crops and varieties, phytonutrients with the potential to act as antioxidants when consumed regularly. Potatoes continue a staple crop in the United States, contributing a large proportion of the total vegetable nutrient intake of the U.S. population (Brown, 2008). Much debate regarding the relative nutritional value of organic food consumption continues, but evidence indicating distinct differences between foods produced organically and foods grown using conventional (synthetic) agricultural fertility inputs is increasing. From the literature currently available, organically fertilized potatoes tend to contain higher levels of the antioxidant vitamin C and higher in a number of specific minerals than potatoes grown with synthetic fertilizers. The theory often cited to describe why organic produce can be higher in essential human nutrients per unit of food relates to a dilution effect. This is a situation in which a plant provided with nutrients in luxurious amounts and in forms rapidly available can set a large number of fruits, causing the plant to partition available nutrients into the forming fruits and dilute the overall nutrient content of each individual fruit. Increased micronutrient and phytochemical concentrations are often seen within organically produced foods, as compared to conventionally produced food. The case regarding organic vs. conventional fertility management and potato nutritive values is not final, but there are some strong indicators in the literature which show the potential for producing a more nutrient dense potato within organic systems.

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Addendum II: **CHANGE IN SOIL FERTILITY STATUS RESULTING FROM COVER CROP GROWTH AND/OR INCORPORATION AS GREEN MANURE**

INTRODUCTION

Cover crop growth has the potential to influence nutrient availability to subsequent crops, either by making nutrients more available for immediate uptake, or by immobilizing nutrients in forms that would require mineralization prior to plant uptake by future crops. Selection of specific crop cultivars to establish a soil environment most suitable to the crop that follows is an outcome desired, and of interest where crop rotation selection for the purpose of building soil productivity is actively engaged. Many novel cultivars have become available for use in cover crop plantings in the San Luis Valley of Colorado, necessitating evaluation of those on offer to determine whether they contribute to the overall fertility of the soils in which they grow.

Research Goal and Objectives

The goal of this research was to identify best cover crop options for use in short season potato production, utilizing the San Luis Valley of Colorado as a test location.

Two specific objectives were to:

1. Evaluate rotational crops and cultivars available to San Luis Valley potato farmers for impact on soil fertility.
2. Describe potential benefits and/or limitations to implementation of alternate rotational crops and cultivars into the cropping system of the San Luis Valley.

MATERIALS AND METHODS

During the summers of 2012 and 2013, field trials utilizing 12 ft x 30 ft small plots replicated 5 times each, were planted in the San Luis Valley of Colorado, into a Gunbarrel sandy loam soil irrigated via center pivot with water from an unconfined alluvial aquifer, with water originally sourced from the Rio Grande River. Plants trialed between 2012 and 2013 were: Cool Season Grasses cereal rye cultivar (cv.) 'Elbon', black oats cv. 'Soil Saver', forage oats cv. 'Monida'; Brassicas arugula cv. 'Trio', Ethiopian cabbage cv. 'Corrine', forage radish cvs. 'Biofum', 'Cassius', 'Defender', 'Terra Nova', Indian mustard cvs. 'Caliente 61' and 'Pacific Gold', Turnip x Kale Hybrid cv. 'Winfred'; Summer Annual Forb buckwheat cv. 'Mancan'; Legume chickling vetch cv. 'AC Greenfix', fava bean cv. 'Snowbird', forage pea cv. '4010', yellow sweet clover cvs. 'vns' and 'YSC-TH Line'.

Planting occurred during early June of both years. The 2012 trial was conducted within a field planted to potatoes for commercial production, and so was irrigated and fertilized according to the requirements of the potato crop. The 2012 trial area did not receive pre-plant fertilizer, but did receive 30 lbs N/acre delivered via fertigation during the period of mid-June to early July. The 2012 study was grown for 86 days, with a total accumulation of 1,208 growing degree days (GDD) base temp 50 degrees F experienced by the crop as measured from aboveground temperatures. The effective precipitation and irrigation amounts received by the cover crop plots totaled 14.3 inches of water. Growth of both crops planted and of weeds emerging from the soil's seedbank was overall very good. Weed control in the 2012 trial was undertaken by hand-pulling weeds, primarily redroot pigweed (*Amaranthus retroflexus*), to limit the amount of seeds that would be produced in the trial area. During the 2013 trial, the trial area was located within a field seeded to sorghum-sudangrass and fodder radish, destined for short-season production and green manuring. The 2013 trial grew for 43 days, experiencing 681 GDD, and 6.9 inches of effective precipitation and irrigation water. No supplemental fertilizers were applied either pre-plant or during the growing season.

Prior to planting of each crop, ten soil cores were taken from each plot, sampling from the soil surface to a depth of 12 inches. These soil cores were mixed, dried and shipped to ServiTech Labs in Amarillo, Texas for chemical analysis which included nitrate-N, P, K, organic matter (loss-on-ignition method), sulfate-S, Ca, Mg, Na, Fe, B, Mn, Cu, Zn, soluble salts, free lime, cation exchange capacity by summation, and potassium permanganate extracted light-fraction carbon (POXC). Sampling from these sample plots occurred prior to incorporation of the standing crop in 2012, and again three weeks after the crop had been chopped and disced into the soil in both 2012 and 2013. Statistical analysis on the soil fertility data was performed using The SAS System, General Linear Model to accommodate unequal sample sizes resulting from limitations to funding and due to errors of cross-contamination within a small number of plots (replicate data from contaminated plots not included in analysis). Measurements of aboveground plant biomass as fresh weight were taken at the end of each trial, with approximations of yield as hay equivalent calculated.

RESULTS AND DISCUSSION

Data from the initial pre-plant soil test, and the relative change between sampling events which followed, are included in Tables 7 and 8. Approximations of total aboveground yield, expressed as tons of hay equivalent 20% moisture per acre, are included in Table 9. This data was generated utilizing fresh weight samples from plots, calculating a hay weight equivalent, as this is the condition of hay sold within the region of the San Luis Valley of Colorado.

Table 7. Change in fertility status of soil in response to cover crop growth and/or incorporation - 2012.

2012 Preplant Soil Fertility Means Table

Crop	Cultivar	N	Soil pH	Sol.Salts mmho/cm	Free Lime	OM %	ppm NO3-N
Cereal Rye	Elbon	5	7.9	0.5	0.2	0.9	23
Chickling Vetch	AC Greenfix	4	7.8	0.5	0.0	0.9	23
Fodder Radish	Defender	3	7.8	0.6	0.0	0.8	29
Forage Oats	Monida	5	7.8	0.8	0.0	0.9	28
Forage Pea	4010	5	7.8	0.7	0.2	0.9	28
Indian Mustard	Caliente 61	4	7.8	0.7	0.0	0.9	32
Indian Mustard	Pacific Gold	3	7.8	0.6	0.0	0.8	26
Sorghum-Sudangrass	Sordan 79	5	7.8	0.6	0.0	0.9	30
Turnip x Kale Hybrid	Winfred	5	7.9	0.5	0.2	0.8	23
Yellow Sweet Clover	vns	4	7.9	0.6	0.0	0.8	30

2012 PreIncorporation minus PrePlant Values

Crop	Cultivar	Soil pH	*	Sol.Salts mmho/cm	Free Lime	OM %	ppm NO3-N
Cereal Rye	Elbon	0.1	D	-0.4	0.4	-0.2	-23
Chickling Vetch	AC Greenfix	0.3	BCD	-0.3	0.0	-0.3	-23
Fodder Radish	Defender	0.3	BCD	-0.4	0.0	-0.2	-28
Forage Oats	Monida	0.3	BCD	-0.6	0.2	-0.3	-28
Forage Pea	4010	0.3	ABC	-0.5	0.4	-0.3	-27
Indian Mustard	Caliente 61	0.4	AB	-0.6	0.5	0.4	-32
Indian Mustard	Pacific Gold	0.4	A	-0.5	0.3	-0.2	-26
Sorghum-Sudangrass	Sordan 79	0.4	AB	-0.4	0.2	-0.2	-29
Turnip x Kale Hybrid	Winfred	0.3	ABC	-0.4	-0.2	-0.2	-23
Yellow Sweet Clover	vns	0.2	BCD	-0.4	1.0	-0.4	-30

* Significant at the 0.05 level, indicated by letters following numbers. Values reported with no letter following are not significantly different

2012 PostIncorporation minus PreIncorporation Values

Crop	Cultivar	Soil pH	Sol.Salts mmho/cm	Free Lime	OM %	ppm NO3-N	*
Cereal Rye	Elbon	-0.1	0.3	-0.6	0.2	7	DE
Chickling Vetch	AC Greenfix	-0.3	0.3	0.8	0.3	15	AB
Fodder Radish	Defender	-0.2	0.1	0.0	0.3	8	DE
Forage Oats	Monida	-0.2	0.1	-0.2	0.4	5	E
Forage Pea	4010	-0.3	0.3	0.2	0.3	20	A
Indian Mustard	Caliente 61	-0.4	0.2	-0.3	-0.3	13	BCD
Indian Mustard	Pacific Gold	-0.3	0.1	-0.3	0.3	6	E
Sorghum-Sudangrass	Sordan 79	-0.2	0.1	0.0	0.3	4	E
Turnip x Kale Hybrid	Winfred	-0.3	0.2	0.0	0.2	9	CDE
Yellow Sweet Clover	vns	-0.3	0.1	0.0	0.5	14	BC

2012 PostIncorporation minus PrePlant Values

Crop	Cultivar	Soil pH	Sol.Salts mmho/cm	*	Free Lime	OM %	ppm NO3-N	*
Cereal Rye	Elbon	0.0	-0.1	AB	-0.2	0.0	-16	BCD
Chickling Vetch	AC Greenfix	0.0	0.0	A	0.8	0.0	-8	AB
Fodder Radish	Defender	0.1	-0.3	ABCD	0.0	0.1	-20	CDE
Forage Oats	Monida	0.1	-0.5	D	0.0	0.0	-23	DE
Forage Pea	4010	0.0	-0.2	ABC	0.6	0.0	-6	A
Indian Mustard	Caliente 61	0.0	-0.3	BCD	0.3	0.1	-19	CDE
Indian Mustard	Pacific Gold	0.1	-0.4	CD	0.0	0.1	-20	CDE
Sorghum-Sudangrass	Sordan 79	0.2	-0.3	BCD	0.2	0.0	-25	E
Turnip x Kale Hybrid	Winfred	0.0	-0.2	ABC	-0.2	0.1	-14	ABC
Yellow Sweet Clover	vns	0.0	-0.3	BCD	1.0	0.2	-16	BCD

Table 7. Change in fertility status of soil in response to cover crop growth and/or incorporation 2012 (continued).

2012 Preplant Soil Fertility Means Table (continued)

Crop	Cultivar	N	lbs NO3-N/ac		ppm P	ppm K		ppm S	lbs S/ac	ppm Ca	ppm Mg	ppm Na		ppm Zn
Cereal Rye	Elbon	5	83		133	355		128	461	2395	212	92		3.7
Chickling Vetch	AC Greenfix	4	81		136	316		126	453	2158	203	91		3.7
Fodder Radish	Defender	3	105		137	302		148	533	2061	186	91		4.0
Forage Oats	Monida	5	102		129	296		223	800	2463	198	104		3.7
Forage Pea	4010	5	101		121	321		243	876	2498	206	103		3.5
Indian Mustard	Caliente 61	4	114		112	330		195	703	2531	205	97		3.7
Indian Mustard	Pacific Gold	3	95		123	310		152	546	2341	206	101		3.6
Sorghum-Sudangrass	Sordan 79	5	107		137	305		173	623	2226	199	95		3.9
Turnip x Kale Hybrid	Winfred	5	82		133	316		139	502	2222	202	92		3.4
Yellow Sweet Clover	vns	4	109		137	329		173	623	2389	214	104		3.7

2012 PreIncorporation minus PrePlant Values (continued)

Crop	Cultivar		lbs NO3-N/ac		ppm P	ppm K		ppm S	lbs S/ac	ppm Ca	ppm Mg	ppm Na	*	ppm Zn
Cereal Rye	Elbon		-83		-16	-34		-103	-372	-105	-11	-27	BCD	0.3
Chickling Vetch	AC Greenfix		-81		-13	-52		-91	-327	-286	-26	-12	AB	0.0
Fodder Radish	Defender		-105		-9	-13		-116	-419	-24	-4	-7	A	0.3
Forage Oats	Monida		-102		-1	-28		-181	-649	-254	-20	-29	BCD	0.4
Forage Pea	4010		-96		-8	-40		-197	-711	-92	-9	-31	CD	0.3
Indian Mustard	Caliente 61		-114		-15	-32		-168	-606	15	0	-28	BCD	0.3
Indian Mustard	Pacific Gold		-95		-9	-29		-127	-459	-162	-11	-36	D	0.5
Sorghum-Sudangrass	Sordan 79		-105		-18	-54		-133	-479	-67	-14	-25	BCD	0.1
Turnip x Kale Hybrid	Winfred		-82		2	-29		-115	-412	-161	-15	-14	ABC	0.8
Yellow Sweet Clover	vns		-109		-30	-28		-117	-422	99	-19	-25	BCD	0.2

* Significant at the 0.05 level, indicated by letters following numbers. Values reported with no letter following are not significantly different

2012 PostIncorporation minus PreIncorporation Values (continued)

Crop	Cultivar		lbs NO3-N/ac	*	ppm P	ppm K		ppm S	lbs S/ac	ppm Ca	ppm Mg	ppm Na		ppm Zn
Cereal Rye	Elbon		27	DE	1	28	BC	82	296	-59	-6	25		-1.1
Chickling Vetch	AC Greenfix		54	AB	-22	48	ABC	321	1156	726	22	17		-0.7
Fodder Radish	Defender		31	DE	-7	87	AB	14	51	69	1	11		-1.4
Forage Oats	Monida		19	E	2	97	A	91	329	288	19	20		-0.4
Forage Pea	4010		74	A	-26	75	AB	132	475	115	13	41		-0.5
Indian Mustard	Caliente 61		47	BCD	24	100	A	60	215	-112	1	29		-0.7
Indian Mustard	Pacific Gold		23	E	8	76	AB	42	152	126	7	33		-1.0
Sorghum-Sudangrass	Sordan 79		14	E	25	74	AB	7	24	-116	-2	8		-0.5
Turnip x Kale Hybrid	Winfred		33	CDE	-3	42	ABC	54	194	-204	-13	3		-0.6
Yellow Sweet Clover	vns		52	BC	13	75	AB	38	138	37	13	16		-0.2

2012 PostIncorporation minus PrePlant Values (continued)

Crop	Cultivar		lbs NO3-N/ac	*	ppm P	ppm K		ppm S	lbs S/ac	ppm Ca	ppm Mg	ppm Na		ppm Zn
Cereal Rye	Elbon		-56	BCD	-15	-6		-21	-76	-165	-16	-2		-0.7
Chickling Vetch	AC Greenfix		-27	AB	-35	-3		230	829	440	-4	4		-0.6
Fodder Radish	Defender		-74	CDE	-16	74		-102	-368	45	-3	4		-1.1
Forage Oats	Monida		-83	DE	1	69		-89	-320	34	0	-9		0.0
Forage Pea	4010		-22	A	-34	34		-65	-235	23	4	9		-0.3
Indian Mustard	Caliente 61		-67	CDE	9	69		-109	-391	-97	1	1		-0.5
Indian Mustard	Pacific Gold		-72	CDE	-1	47		-85	-307	-37	-4	-3		-0.6
Sorghum-Sudangrass	Sordan 79		-91	E	7	20		-126	-455	-183	-16	-16		-0.4
Turnip x Kale Hybrid	Winfred		-49	ABC	-1	13		-61	-219	-365	-28	-11		0.3
Yellow Sweet Clover	vns		-57	BCD	-17	47		-79	-285	137	-6	-9		0.0

Table 7. Change in fertility status of soil in response to cover crop growth and/or incorporation 2012 (continued).

2012 Preplant Soil Fertility Means Table (continued)

Crop	Cultivar	N	ppm Fe	ppm Mn	ppm Cu	CEC	%K	%Ca	%Mg	%Na	Boron (ppm)	POXC (ppm)
Cereal Rye	Elbon	5	6.4	9.8	1.5	15	6	79	12	3	2.0	132
Chickling Vetch	AC Greenfix	4	6.3	10.5	1.5	14	6	79	13	3	2.3	155
Fodder Radish	Defender	3	6.0	10.0	1.6	13	6	79	12	3	2.1	153
Forage Oats	Monida	5	5.8	9.6	1.4	15	5	81	11	3	2.2	147
Forage Pea	4010	5	6.0	10.0	1.5	16	6	80	11	3	2.1	141
Indian Mustard	Caliente 61	4	6.3	9.8	2.1	16	6	81	11	3	2.3	144
Indian Mustard	Pacific Gold	3	6.0	9.3	1.4	15	5	80	12	3	2.3	144
Sorghum-Sudangrass	Sordan 79	5	6.2	10.2	1.3	14	6	80	12	3	2.3	153
Turnip x Kale Hybrid	Winfred	5	5.8	7.6	1.2	14	6	79	12	3	2.4	142
Yellow Sweet Clover	vns	4	6.0	10.0	1.3	15	6	80	12	3	2.6	154

2012: PreIncorporation minus PrePlant Values (continued)

Crop	Cultivar	ppm Fe	ppm Mn	ppm Cu	CEC	%K	%Ca	%Mg	%Na	Boron (ppm)	POXC (ppm)
Cereal Rye	Elbon	-0.8	-0.6	0.4	-1	0	1	0	-1	-0.3	21
Chickling Vetch	AC Greenfix	-1.0	-4.8	0.2	-2	0	0	0	0	-0.7	-9
Fodder Radish	Defender	-1.0	-3.3	0.3	0	0	0	0	0	-0.4	-10
Forage Oats	Monida	-0.6	-4.2	0.9	-2	0	0	0	-1	-0.5	6
Forage Pea	4010	-0.4	-3.6	-0.1	-1	-1	1	0	-1	-0.4	1
Indian Mustard	Caliente 61	-1.3	-3.3	-0.6	0	-1	1	0	-1	-0.5	28
Indian Mustard	Pacific Gold	-1.0	-3.0	0.3	-1	0	1	0	-1	-0.5	7
Sorghum-Sudangrass	Sordan 79	-1.0	-3.2	0.5	-1	-1	1	0	-1	-0.2	-3
Turnip x Kale Hybrid	Winfred	-0.2	-1.6	0.7	-1	0	0	0	0	-0.5	6
Yellow Sweet Clover	vns	-1.0	-4.5	1.2	0	0	2	-1	-1	-0.7	-21

* Significant at the 0.05 level, indicated by letters following numbers. Values reported with no letter following are not significantly different

2012: PostIncorporation minus PreIncorporation Values (continued)

Crop	Cultivar	ppm Fe	ppm Mn	*	ppm Cu	CEC	%K	%Ca	%Mg	%Na	Boron (ppm)	POXC (ppm)
Cereal Rye	Elbon	-0.8	-4.2	D	-0.9	0	1	-1	0	0	-0.9	328
Chickling Vetch	AC Greenfix	-1.0	-1.0	AB	-0.7	4	0	1	-1	-1	-1.0	290
Fodder Radish	Defender	-2.0	-2.7	BCD	-1.1	0	1	-1	0	0	-1.0	322
Forage Oats	Monida	-0.6	0.0	A	-1.1	2	1	-1	-1	0	-0.9	328
Forage Pea	4010	-1.6	-2.0	ABCD	-0.5	1	1	-2	0	1	-0.8	352
Indian Mustard	Caliente 61	-0.8	-1.8	ABCD	-0.5	0	2	-3	0	1	-1.0	348
Indian Mustard	Pacific Gold	-1.7	-2.3	ABCD	-0.8	1	1	-1	0	1	-1.0	310
Sorghum-Sudangrass	Sordan 79	-1.2	-1.2	ABC	-0.8	0	2	-2	0	1	-1.3	302
Turnip x Kale Hybrid	Winfred	-1.2	-0.8	AB	-0.8	-1	1	-2	0	1	-1.1	308
Yellow Sweet Clover	vns	-0.5	-0.3	AB	-1.2	1	1	-2	0	1	-1.1	341

2012: PostIncorporation minus PrePlant Values (continued)

Crop	Cultivar	ppm Fe	ppm Mn	ppm Cu	*	CEC	%K	%Ca	%Mg	%Na	Boron (ppm)	POXC (ppm)
Cereal Rye	Elbon	-1.6	-4.8	-0.6	CDE	-1	1	0	0	0	-1.2	349
Chickling Vetch	AC Greenfix	-2.0	-5.8	-0.5	BCD	2	-1	2	-1	-1	-1.7	281
Fodder Radish	Defender	-3.0	-6.0	-0.8	DE	0	1	-1	-1	0	-1.4	312
Forage Oats	Monida	-1.2	-4.2	-0.3	ABC	1	1	-1	0	0	-1.4	334
Forage Pea	4010	-2.0	-5.6	-0.5	BCDE	0	0	-1	0	1	-1.2	353
Indian Mustard	Caliente 61	-2.0	-5.0	-1.1	E	0	1	-1	0	0	-1.5	376
Indian Mustard	Pacific Gold	-2.7	-5.3	-0.5	BCD	0	1	0	0	0	-1.5	318
Sorghum-Sudangrass	Sordan 79	-2.2	-4.4	-0.3	ABCD	-1	1	-1	0	0	-1.6	299
Turnip x Kale Hybrid	Winfred	-1.4	-2.4	0.0	AB	-2	1	-2	0	0	-1.6	314
Yellow Sweet Clover	vns	-1.5	-4.8	0.0	A	1	1	0	-1	0	-1.8	320

Table 8. Change in fertility status of soil in response to cover crop growth and/or incorporation - 2013.

2013 Preplant Soil Fertility Means Table													
Crop	Cultivar	N	Soil pH	Sol.Salts mmho/cm	Free Lime	OM %	ppm NO3-N	lbs NO3-N/ac	ppm P	ppm K	ppm S	lbs S/ac	ppm Ca
Arugula	Trio	5	7.6	1.3	0.8	0.9	55	198	196	245	330	1190	2737
Black Oats	Soil Saver	5	7.6	1.3	0.4	0.9	50	179	202	230	270	970	2435
Buckwheat	Mancan	5	7.7	1.2	0.6	0.9	44	160	180	220	220	794	2403
Cereal Rye	Elbon	5	7.7	1.2	1.4	0.9	55	196	152	251	252	907	3060
Ethiopian Cabbage	Corrine	5	7.6	1.2	0.2	1.0	47	169	194	227	279	1004	2434
Fava Bean	Snowbird	5	7.6	1.2	0.4	0.9	54	196	206	239	295	1062	2627
Fodder Radish	Biofum	5	7.6	1.3	1.2	0.9	52	186	200	243	284	1024	2681
Fodder Radish	Cassius	5	7.6	1.2	0.6	0.9	57	204	195	250	293	1057	2608
Fodder Radish	Defender	5	7.6	1.1	1.2	0.9	54	196	172	245	262	942	2773
Fodder Radish	Doublet	5	7.6	1.3	0.6	0.9	44	158	190	218	299	1076	2362
Fodder Radish	Terra Nova	5	7.6	1.1	0.2	0.9	46	164	198	212	242	872	2199
Forage Oat	Monida	5	7.6	1.3	0.4	0.9	51	184	191	235	312	1122	2667
Indian Mustard	Caliente 61	5	7.6	1.4	0.4	0.9	47	168	190	199	337	1214	2522
Pearl Millet	TiffLeaf3	5	7.6	1.4	1	0.9	54	195	184	226	304	1097	2418
Yellow Sweet Clover	YSC - TH Line	5	7.6	1.3	0.4	0.9	46	166	184	225	323	1164	2599

2013 PostIncorporation Minus PrePlant Values *													
Crop	Cultivar		Soil pH	Sol.Salts mmho/cm	Free Lime	OM %	ppm NO3-N	lbs NO3-N/ac	ppm P	ppm K	ppm S	lbs S/ac	ppm Ca
Arugula	Trio		0.2	0.0	-0.6	0.0	-1	-4	-48	34	99	356	260
Black Oats	Soil Saver		0.2	-0.2	-0.4	0.1	17	60	-41	155	-81	-292	108
Buckwheat	Mancan		0.1	-0.1	-0.6	0.0	12	44	-28	72	-11	-39	312
Cereal Rye	Elbon		0.1	0.0	-0.2	0.0	-2	-6	-27	63	-3	-12	134
Ethiopian Cabbage	Corrine		0.2	-0.4	-0.2	0.0	2	6	-26	111	-90	-323	-38
Fava Bean	Snowbird		0.2	0.0	-0.4	0.1	5	19	-53	123	-24	-89	171
Fodder Radish	Biofum		0.2	-0.3	-1.2	0.0	-10	-37	-50	118	-89	-318	-77
Fodder Radish	Cassius		0.1	0.1	-0.6	0.0	-3	-11	-41	47	-46	-167	-69
Fodder Radish	Defender		0.2	-0.1	-0.6	0.1	4	14	-28	82	-42	-150	80
Fodder Radish	Doublet		0.2	-0.2	-0.6	0.0	0	0	-36	85	-62	-222	31
Fodder Radish	Terra Nova		0.3	-0.3	-0.2	0.1	9	31	-41	185	-129	-464	111
Forage Oat	Monida		0.2	-0.1	-0.4	0.0	2	6	-43	74	-48	-172	6
Indian Mustard	Caliente 61		0.2	-0.2	-0.4	0.1	11	41	-43	130	-122	-439	68
Pearl Millet	TiffLeaf3		0.2	-0.1	-0.8	0.1	7	27	-32	122	-116	-423	95
Yellow Sweet Clover	YSC - TH Line		0.2	-0.2	-0.4	0.0	-6	-21	-28	86	-92	-328	-28

* No statistical differences found at 0.05 level between cultivars across analytes.

Table 8. Change in fertility status of soil in response to cover crop growth and/or incorporation - 2013.

2013 Preplant Soil Fertility Means Table (continued)															
Crop	Cultivar	ppm Mg	ppm Na	ppm Zn	ppm Fe	ppm Mn	ppm Cu	CEC	%K	%Ca	%Mg	%Na	Boron (ppm)	POXC (ppm)
Arugula	Trio	241	151	4.7	6	7	1.0	17	4	81	12	4	0.7	230
Black Oats	Soil Saver	234	144	4.5	5	7	1.1	15	4	79	13	4	0.7	210
Buckwheat	Mancan	215	133	4.2	6	7	1.0	15	4	80	12	4	0.7	198
Cereal Rye	Elbon	242	146	4.2	6	7	1.1	19	3	82	11	4	0.7	216
Ethiopian Cabbage	Corrine	239	146	4.7	6	7	1.0	15	4	79	13	4	0.7	216
Fava Bean	Snowbird	238	148	5.3	6	7	1.2	16	4	80	12	4	0.6	215
Fodder Radish	Biofum	242	150	4.3	5	7	1.0	17	4	80	12	4	0.6	216
Fodder Radish	Cassius	240	151	4.5	6	8	1.0	16	4	80	12	4	0.7	244
Fodder Radish	Defender	234	144	4.6	6	8	1.0	17	4	81	12	4	0.6	167
Fodder Radish	Doublet	233	147	4.5	6	6	1.0	15	4	79	13	4	0.6	220
Fodder Radish	Terra Nova	224	134	4.7	6	7	0.9	14	4	79	13	4	0.6	207
Forage Oat	Monida	245	151	4.4	5	7	0.9	17	4	80	12	4	0.7	232
Indian Mustard	Caliente 61	227	146	4.4	6	6	1.0	16	3	81	12	4	0.6	206
Pearl Millet	TiffLeaf3	228	144	4.5	6	7	0.9	15	4	80	12	4	0.7	239
Yellow Sweet Clover	YSC - TH Line	250	156	4.9	6	7	1.0	16	4	79	13	4	0.6	218

2013 PostIncorporation Minus PrePlant Values * (continued)														
Crop	Cultivar	ppm Mg	ppm Na	ppm Zn	ppm Fe	ppm Mn	ppm Cu	CEC	%K	%Ca	%Mg	%Na	Boron (ppm)	POXC (ppm)
Arugula	Trio	23	5	-0.2	2	-2	0.0	2	0	0	0	0	0.1	54
Black Oats	Soil Saver	16	-41	0.0	2	0	0.2	1	2	-1	0	-1	0.1	100
Buckwheat	Mancan	30	1	0.2	2	-1	0.1	2	0	0	0	-1	0.2	86
Cereal Rye	Elbon	11	-13	-0.1	1	-1	0.0	1	1	-1	0	-1	0.1	65
Ethiopian Cabbage	Corrine	2	-39	0.2	3	0	0.2	0	2	-1	0	-1	0.1	71
Fava Bean	Snowbird	20	-22	-0.8	2	-1	0.1	1	2	-1	0	-1	0.4	52
Fodder Radish	Biofum	6	-34	0.0	2	-1	-0.1	0	2	-1	0	-1	0.2	80
Fodder Radish	Cassius	4	-18	-0.1	2	-2	0.0	0	1	-1	1	-1	0.0	32
Fodder Radish	Defender	12	-15	-0.4	2	-2	0.0	1	1	-1	0	-1	0.5	108
Fodder Radish	Doublet	2	-27	-0.4	2	-1	0.4	0	1	0	0	-1	0.6	38
Fodder Radish	Terra Nova	28	-25	-0.9	0	-2	0.0	1	3	-2	1	-1	0.0	121
Forage Oat	Monida	-1	-10	0.0	3	-1	0.2	0	1	0	0	0	0.0	79
Indian Mustard	Caliente 61	13	-22	0.3	1	0	0.2	1	2	-1	0	-1	0.2	89
Pearl Millet	TiffLeaf3	13	-28	0.1	2	1	0.3	1	2	-1	0	-1	0.2	70
Yellow Sweet Clover	YSC - TH Line	-7	-36	0.2	3	-1	0.3	0	1	0	0	-1	0.0	57

* No statistical differences found at 0.05 level between cultivars across analytes.

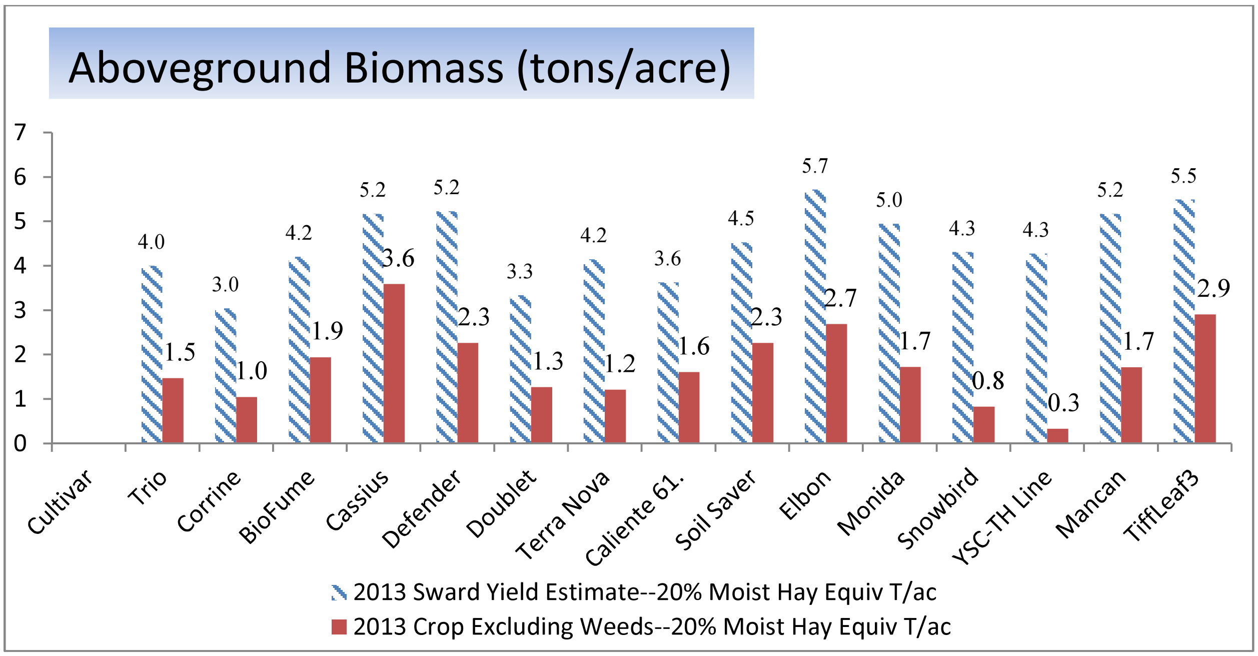
Table 9. Approximate yield of cover crop aboveground biomass, as 20 percent moisture hay equivalent if baled.

Crop	Cultivar	tons hay equivalent/acre *	
		2012	2013
Arugula	Trio	---	0.8
Black Oat	Soil Saver	---	0.7
Buckwheat	Mancan	---	0.5
Cereal Rye	Elbon	2.5	0.9
Chicklig Vetch	AC-Greenfix	3.6	---
Ethiopian Cabbage	Corrine	2.6	0.5
Fava Bean	Snowbird	---	0.2
Fodder Radish	Biofum	---	1.0
Fodder Radish	Cassius	---	1.8
Fodder Radish	Defender	2	1.3
Fodder Radish	Doublet	3.6	0.6
Fodder Radish	Terra Nova	---	0.6
Forage Oat	Monida	2.9	0.6
Forage Pea	4010	3.6	---
Indian Mustard	Caliente 61	3	0.8
Indian Mustard	Pacific Gold	4.6	---
Pearl Millet	TiffLeaf3	---	1.0
Sorghum-Sudangrass	Sordan 79	2.7	---
Turnip x Kale Hybrid	Winfred	1.8	---
Yellow Sweet Clover	vns	1.7	---
Yellow Sweet Clover	YSC-TH Line	---	0.2

* approximation based on wet forage sample weights

Variability in crop growth relative to weed growth was great across plots (Figure 1), resulting in wide variation in yield per plot and per treatment replicate. Mean values of approximate hay equivalents are used in Table 9 for demonstrative purposes in this report. The great difference in estimated biomass between the years is largely due to the especially long, warm and moist growing season experienced in 2012's trial, contrasted by the particularly short season of growth afforded all plots in 2013. One of the outcomes in maintaining the plots alive for an especially brief period was that the annual weeds which normally flourish in such settings were not able to make viable seed in the time allotted the cover crop to grow in 2013. This is of importance where weed suppression is employed as a primary practice in an integrated pest management strategy within crop rotations.

Figure 1. 2013 aboveground biomass from weeds and cover crops.



The analysis of variance using the General Linear Model, applying significance at p <= 0.05, allowed distinctions to be drawn in the comparison of soil fertility at distinct moments during the year. In 2012, soil pH values under the 'Elbon' cereal rye treatment increased very slightly (pH change = 0.1), while Forage Pea '4010', Indian Mustards 'Calinete 61' and 'Pacific Gold', Sorghum-Sudangrass Hybrid 'Sordan 79', and Turnip x Kale cross 'Windred' experienced rises between pH 0.3 – 0.4 above the beginning levels near pH 7.8. The Gunbarrel sandy loam soil is highly buffered with bases, and irrigation water in the area tends to be basic and laden with bases, as well. Based on knowledge of the root systems of each of these crops, it is possible the cereal rye cultivar is distributing more effectively acid-forming root exudates into the rhizosphere due to its normally massive rooting extent. Unexpected was the result of ‘Sordan 79’, also a plant with a very active root system, but with a response in which the pH has risen prior to incorporation of the aboveground residues into the soil.

A general decrease in the sodium concentration occurred over the span of the 2012 trial period from pre-plant to the time just before incorporation of the biomass (pre-incorporation), with sodium levels decreasing, likely due to root growth forming pathways for sodium to leach deeper into the profile. A curious result is found in the greatest decrease in Na came from soil in which the brassica ‘Pacific Gold’ Indian Mustard was growing, and at the same instant another brassica, the ‘Defender’ radish, showed the least decrease in sodium. Sodium accumulation is a concern in the arid western USA, including in the San Luis Valley of Colorado where large areas are irrigated with groundwater that is somewhat impaired by sodium-loading.

Looking to the data from the 2012 post-incorporation minus pre-incorporation soil analyses, in the period of three weeks of mild (approximately 70 degrees F day / 38 degrees F night) late summer temperatures of the San Luis Valley, nitrogen release in the form of nitrate began to express from the 2012 trial, with legumes AC Greenfix, showing a significantly higher N contribution to the soil than the grasses, and higher than the ‘Pacific Gold’ and ‘Defender’ brassicas which by that point in the season were in full flower and beginning to become lignified (developing high C:N ratio, relative to legumes). Looking at the data from the post-incorporation minus pre-plant soil analyses, there appears to be a net capture of nitrogen in the biomass of the plants incorporated, with the exception of the forage pea ‘4010’ and chickling vetch ‘AC Greenfix’.

The quick release of plant available nitrogen from ‘4010’ and ‘AC Greenfix’ may not be of great value to the following cash crop of potatoes, however, as many months and multiple opportunities for moderate precipitation events to leach the nitrate deep into the soil will pass between a late summer incorporation of cover crop residues and the eventual spring planting of potatoes. Utilizing a mix of cover crops, which include these legumes but also some portion of higher C:N producing plants such as grasses or long-growing brassicas may serve to hold in the topsoil the nitrogen fixed by the previous season’s legume, and to release it in time to benefit the potatoes which will follow. The relative neutral performance of the legume yellow sweet clover ‘vns’ is likely due to the biennial growth habit of this legume, in which its biomass and nitrogen fixation potential are limited in its first summer of growth, but compensating well in its ability to produce biomass and fix nitrogen in the spring and summer of its second growing season. Biennial legumes may be of use in potato rotations to help bolster biologically fixed nitrogen where they can be left to grow long into the spring, being incorporated immediately prior to potato planting. Having said that, other factors, including Columbia root knot nematode host status, must be considered when devising a cropping sequence that will span many months, should Columbia root knot nematode be a pest of concern to the field in question.

Copper availability appears to be suppressed soon after incorporation of biomass, as seen in the post-incorporation minus pre-plant values. This effect is expected to be a temporary immobilization reliant upon moist, warm soil conditions to affect mineralization of this nutrient. The cultivars ‘Winfred’ and yellow sweet clover ‘vns’ held copper availability well, while the brassica ‘Caliente 61’ had significantly more tie up of copper at the time of post-incorporation sampling. Another metal micronutrient, manganese, showed a significant decline in availability under the ‘Elbon’ cereal rye treatments, while the ‘Monida’ forage oats held steady with effectively no change in the post-incorporation minus pre-incorporation values. Again, this response is expected to be temporary and not to impact the nutrient availability of manganese to the potato crop come spring. Both of these metal micronutrients have decreased availability as soil pH increases above pH 7.0.

The soil fertility data from the 2013 field trial did not show significant differences between treatments. Likely this lack of significance is a result of two factors: immense variability in seeded crop growth and variability in competition with weeds, and the short growth cycle managed for the trial in that year.

CONCLUSIONS

Nitrogen release rate following incorporation of legumes into the soil will need to be managed with care, looking to the C:N ratio of the mix being incorporated, to assure potential benefits from having growing a N-fixing crop may be reaped in the catching and releasing of that nitrogen when it will be of use, months later in the spring. Utilization of mixtures of low C:N, and of moderate C:N crop residues will be an important tool for managing nitrogen release timing, but also for sustaining soil microbial populations on more resilient carbonaceous plant materials for their food, to sustain nutrient cycling and beneficial soil microbial communities beyond the brief time following the growth and incorporation of the cover crop.

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