DISSERTATION

Potential Use of Variety and Crop Rotation as Tools for Agricultural Sustainability

Submitted by

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In partial fulfillment of the requirements

for the Degree of Doctor of Philosophy

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY ABDULLAH A. AL-SHEIKH ENTITLED POTENTIAL USE OF VARIETY AND CROP ROTATION AS TOOLS FOR AGRICULTURAL SUSTAINABILITY BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

Potential Use of Variety and Crop Rotation as Tools for Agricultural Sustainability

Since it has been reported that NUE for potatoes (*Solanum tuberosum* L.) are lower than those of small grains (such as wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.) and that the potential for wind erosion for potato systems, which leave small quantities of crop residue after harvest, is higher than those for small grains, we studied the potential to use potato varieties to increase NUE and crop rotations to protect soil and water quality. These studies were conducted at Colorado State University and in the San Luis Valley (SLV) of South Central Colorado.

Physiological parameters such as rate of N uptake was more important for smaller rooted potato varieties while morphological parameters such as root surface area and length were more important for varieties with larger rooting systems. The Nutrient Efficiency Ratio (g tuber/g N uptake) of 277 for Norkota-Line 8 was higher than the 246 for Nugget ($P < 0.05$). The Norkota-Line 8 was more efficient in using a unit of N to produce a unit of yield. Although Norkota-Line 8 had a smaller root surface area it was a more efficient variety and had a higher N recovery and N removal (N harvested in tubers) from the field than Nugget. Higher tuber production can contribute to reduce N losses to the environment and increase NUE.

Mean crop C residue returned to the soil reduced wind erosion and was also correlated with the percentage of silt and clay ($r^2=0.99$; $P < 0.01$). Crop residue returned to the soil was also positively correlated with the SOM-C ($r^2=0.99$; $P < 0.01$) and SOM-N content ($r^2=0.99$; $P < 0.01$). When we added about 2.5 t C ha^{-1} y^{-1} with the small grain

crop residue we increased the level of SOM for these coarse sandy soils. There is potential to use cropping systems and varieties as universal tools to increase recoveries of N and conserve water quality by sequestering N in the soil organic matter, thereby reducing N losses to the environment, reducing erosion and increasing agricultural sustainability.

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Finally, heartfelt thanks to my wife and my children for their patience, support, smiles and understanding during the past four years of my study.

SPECIAL DEDICATION

I wish to dedicate this dissertation to the memory of my parents who passed away while I was a child. I also dedicate this scientific work to my family, my wife Zahar, and my sons Musaed, Mohammed and Hisham and my daughters Afnan and Banan who came with me to the USA and encouraged me during my study years at Colorado State University.

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CHAPTER I

Assessment of Potato Root Properties on Nitrogen Uptake†[1]

ABSTRACT

Nitrogen (N) use efficiencies (NUE) are on average 50% indicating a need to continue developing new Best Management Practices (BMPs) that can increase NUE and economic return to farmers. There is the need to develop varieties that can potentially minimize N losses and conserve water quality and agricultural sustainability. To understand how varieties can be used to improve NUE additional information about the effects of root physiological and morphological parameters on rate of N uptake is needed, especially of potato (*Solanum tuberosum* L.) varieties with shallower rooting systems that are more susceptible to N losses. Russet Norkota-line 8 and Russet Nugget varieties were grown in two greenhouse studies at Colorado State University and in a field study at the San Luis Valley Research Center, Center, Colorado. Root morphological parameters such as diameter, length and surface area were measured. Above- and below-ground biomass, tuber yields and N uptake were also measured. Root morphological parameters (such as a larger root surface) were correlated with the higher N uptake efficiency for Nugget but that the root physiological parameters (such as rate of N influx per root surface area) were higher for the Norkota-line 8 variety. Although the Norkota-line 8 variety had smaller above-ground biomass (15 – 25%) and root surface area (15 – 24%) its C flux through the above-ground plant compartment and the N flux through the root surface area to the tubers

[1] **Chapter submitted for Journal Publication**

were 73 and 100% higher, respectively than those observed for Nugget. Norkota-line 8, although physically smaller and more compact than Nugget, was more efficient in atmospheric C fixation and transport to the tubers, in the rate of N uptake by the root, and in production of higher tuber yields.

Norkota-Line 8 tuber yield of 56 t ha^{-1} (1470 g per plant) was higher than the 41 t ha^{-1} for Nugget (1080 g per plant) ($P < 0.05$). The Nutrient (N) Efficiency Ratio (g tuber/g total N uptake) of 277 for Norkota-Line 8 was higher than the 246 for Nugget ($P < 0.05$). The Norkota-Line 8 was more efficient in using a unit of N to produce a unit of yield. These root studies show the importance of evaluating root morphological and physiological characteristics when developing genotypes for higher N use efficiencies.

Under BMPs that minimize N losses, varieties with larger root surface area or higher rate of N uptake per unit of root surface will have the potential for higher NUE, there by minimizing N losses to the environment. Although root morphological and physiological parameters will contribute to higher NUE, yields will depend on how efficient the variety is in using and translocating of its resources to the root. Although Norkota-Line 8 had a smaller root surface area it was a more efficient variety and had a higher rate of N uptake than Nugget. Higher production and N content in the tubers can contribute to a higher N removal from the field a net higher NUE, reducing N losses to the environment.

ABBREVIATIONS

BMPs, Best management practices

CSU, Colorado State University

NER, Nutrient efficiency ratio

NUE, Nitrogen use efficiency

r_d, Root diameter

r_l, Root length

RNU, Rate of N uptake

r_{sa}, Root surface area

SLV, San Luis Valley

SLVRC, San Luis Valley Research Center

INTRODUCTION

Newbould (1989), Raun and Johnson, (1999), and Delgado, (2002) have reported that assuming a steady state system, N use efficiencies (NUE) on average are about 50% and are equivalent to worldwide global losses of billions of US dollars. It is important to continue developing new tools and best management practices (BMPs) that can increase NUE and economic return to farmers (Delgado et al., 2001*a,b*, 2003). Baligar et al. (2001) reported that one tool that can be used to increase NUE is the selection of varieties with higher NUE. There is the need to develop varieties with lower N use index (N uptake needed to produce one unit of yield) and higher NUE that can potentially contribute to minimize N losses and conserve water quality and agricultural sustainability (Delgado, 2001).

Breeding programs can be used to develop varieties with larger root zone area that can assess higher nutrient and water use with potential to maximize yields at low nutrient levels (Vose, 1984 & 1987; Clark and Duncan, 1991; Sattelmacher et al., 1994; Baligar et al., 2001; Delgado 2001). This is of particular importance for N which is the most dynamic and mobile essential nutrient, with potential to impact air and water quality if transported out of the root zone area (Follett et al., 1991; IPCC 1994).

Delgado (1998, 2001) reported that NO_3-N leaching losses, NUE and potential to scavenge NO_3-N from underground irrigation water were correlated with crop rooting depths. Although there is potential to keep NO_3-N leaching losses below the root zone in irrigated sandy soils to a minimum with proper BMPs (Smika et al., 1977; Hergert, 1986; Westerman et al., 1988; Schepers et al., 1995; Thompson and Doerge, 1996*a,b*), N N management for crops with shallower rooting depths is difficult, especially in irrigated coarse sandy soils with low water holding capacity and higher potential for NO_3-N leaching (Meisinger and Delgado, 2002; Shaffer and Delgado, 2002; Alva et al., 2003).

Management of N with shallower rooted crops in irrigated soils is difficult especially when applied at or before planting (Delgado et al., 1998). Shoji et al. (2001) reported that the NUE of the initially applied N was about 20%, lower than the 66% for the late applied N during the growing season. A similar NUE trend was observed by Westerman et al. (1988) with 60% for the preplant N vs 80% during the growing season N. Shoji et al. (2001) reported that the NUE for controlled slow release fertilizers during the growing season was 60.2% higher than the 46.3% with traditional farmer practices. Errebhi et al. (1998) reported N recoveries of 33% in high rainfall year and 56% in average rain fall year. These studies show that NUE can be increased with split applications applied at planting and during the growing season (DeRoo and Waggoner, 1961; Lesczynski and Tanner, 1976; Delgado, et al., 1998; Shoji et al., 2001; Iritani, 1978; Vitosh and Jacobs, 1990; Westermann et al., 1988).

Mechanistic models have been used to conduct assessment of plant physiological and morphological parameters. The Barber and Cushman (1981) mechanistic model was used to study N, K, P and S (Silberbush and Barber, 1983; Barber, 1984; Delgado and Amacher, 1995 & 1997). The application of this mechanistic model to evaluate the effect of crop physiological and morphological parameters was based on a list of assumptions described in Barber and Cushman (1981) and Barber (1984). They assumed uniform rate of nutrient uptake across all the root surface. They also assumed that the influx of the nutrient as a function of concentration at the root surface was described by a single phase of the Michaelis-Menten kinetics. These basic assumptions were sufficient and not essential to verify the model and to describe the uptake of these nutrients by crops (Silberbush and Barber, 1983, 1984; Barber 1984; Delgado and Amacher 1995, 1997). Sensitivity analyses showed that some of the morphological and physiological parameters were important for nutrient uptake.

A root's morphological or physiological properties can be affected by the growing medium. Baligar et al. (1975) reported that bulk density will affect root anatomy and that cells did not elongate as much as they expanded at higher bulk densities. Peterson and Barber (1981) reported that soybeans grown in sand pots had a wider radius than those grown in solution cultures and that the Influx Maximum was higher in the sand medium. Root physiological parameters such as rate of nutrient uptake were reported to be affected by age (Edwards and Barber, 1976), medium of growth (Peterson and Barber, 1981), and starvation time (Drew et al., 1984). Warncke and Barber (1973, 1974) expressed the rate of N, P, and K in μg of nutrient per day measuring the root length and uptake at several times in the field and the greenhouse.

Nutrient uptake at the root surface is an active process that has been described using a Michaelis-Menten kinetics, a carrier-mediated transport of an ion across a membrane (Jacobson and Overstreet, 1947; Epstein and Hagen, 1952). Several researchers have reported a correlation between the rate of nutrient uptake and above-ground properties. Rajan (1966) reported that S uptake by sunflower increased as transpiration increased. Jensen and Konig (1982) suggested a feedback mechanism between roots and shoots that regulates S translocation to the shoot. The uptake of S was correlated to light and intact roots absorbed higher S than excised roots or plants kept in the dark. Addition of sucrose to plants kept in the dark and excised roots increased S absorption by 10%. These reports show that it is important to consider above-ground properties when evaluating the potential effect of root properties on nutrient uptake. Our goal was to assess the effect of root morphological and physiological parameters on the rate of N uptake (RNU) by potato varieties under controlled conditions in the greenhouse and to conduct an initial assessment under field conditions on their effect of NUE.

MATERIAL AND METHODS

Assessments of potato root properties on N uptake were conducted with two greenhouse studies at Colorado State University, Fort Collins, Colorado and a field study at the CSU San Luis Valley (SLV) Research Center (SLVRC), Center, Colorado. Since field root studies are very intensive and labor and time consuming two greenhouse studies under controlled conditions were conducted, to facilitate the washing and processing of the total root mass. A third study was conducted in the field to assess if observed differences in root parameters among varieties in greenhouse conditions were also observed under field conditions. All studies were conducted in a sandy loam coarse-loamy, mixed, superactive, frigid Typic Haplocalcid located at the SLVRC. Soils for Greenhouse Study one (GS1) and two (GS2) were collected from the SLV at 0-50 cm depth, sieved through 2 mm, mixed and packed to bulk density of 1.43 g cm^{-3}. Soil samples were taken prior to planting and sent to the CSU soil and plant testing laboratory for analysis (Table I.1).

Greenhouse study one (GS1): Potato seeds of Russet Norkota-line 8 and Russet Nugget were grown in a box with vermiculite medium located in the greenhouse and were watered as needed during spring 2001. After germination, seedlings were selected by matching their root length and diameter, separated from the tuber and transplanted into the soil medium, one seedling per 7 L pot. The experimental design was a randomized complete design with four replications. Plants were watered by keeping soil-water content close to field capacity of 15.4% (v/v). The pots were weighed daily and water lost was replenished without exceeding the 15.4% water content.

Shoots were harvested at time zero (transplanting) and at 15 d after planting. Samples were dried at 55°C, weighed, fine ground and sent to CSU Soil and Plant Testing Laboratory for C and N chemical analyses using a LECO CHN-1000 analyzer (LECO Corp., St. Joseph, MI; Yeomans and Bremner, 1991). Roots were picked by washing the soil gently through a 2-mm sieve, stored in a 1:1 (v:v) methyl alcohol:deionized water mixture, and kept in the refrigerator at 4 °C until measurements were conducted. Root length (r_l) and diameter (r_d) were determined by using the Delta-T Scan (Kirchhof and Pendar, 1993). Root surface area was determined using the same equation used for volume by Shenk and Barber (1979), but modified for r_{sa}, with assumption from Barber and Cushman (1981) that roots were perfect cylinders (equation 1). After root measurements were collected, roots were dried at 55 °C and weights were recorded.

$$r_{sa} = \pi \, r_d \, r_l^{0.5} \qquad \text{eq. 1}$$

Greenhouse study two (GS2): Potato seeds of Russet Norkota-line 8 and Russet Nugget were directly planted at 10 cm depths in 172 kg soil can^{-1} with bulk density of 1.43 g cm^{-3} (cans had an average 62 cm height and i.d. of 52 and 44 cm at top and bottom locations, respectively). Fertilizer was added at the rate of 17.4 and 26.1 mg N kg^{-1} which is equivalent to 160 and 240 kg N ha^{-1} on a bulk density basis. The added fertilizers were manually mixed with the soil at a depth of 16 to 32 cm from the can surface. Additionally K_2O, and P_2O_5 was added at the rate of 59 and 56 mg N kg^{-1}, respectively to each can. Plants were grown at the CSU greenhouse from June to August 2002. Water was maintained close to field capacity with the use of tensiometers that were placed at 20, 40 and 60 cm depths. Pots were irrigated by adding water to keep the pots reading above 0.05 MPa during plant growth. Experimental design was a factorial (N fertilizer by variety) block design with three replicates.

Before tuber initiation, plants were harvested. Above-ground plant compartments were sampled and separated from roots. Below-ground stems, stolen and roots were harvested from the soil by cutting the cans in half and washing each half of the can gently with water through a sieve. Below-ground stems and stolen were included with the above-ground plant material. Roots were stored and processed as described above for root measurements. Above-ground plant compartments were processed as described above for dry weights and C and N analysis. A set of cans were left until harvest for fresh and dry matter tuber yield. At harvest the tubers were dug from the can, washed and weighed. The tubers were cut in slices, oven dried, and weighed.

Field study: Potato seeds of Russet Norkota-line 8 and Russet Nugget were directly planted with an eight row planter in plots that were 9.2 m length by 10.4 m wide. Rows were planted at 0.86 m wide. Potatoes were planted in May 1, 2002 and harvested September 15, 2002. Plots were fertilized with 90 kg N ha^{-1} banded at planting. Additionally, six fertigations of 7.5 kg N each were applied for a total of 45 kg N ha^{-1}. Initial and final soil NO_3-N and NH_4-N was measured at the CSU Soil Testing Laboratory.

Root properties were assessed at 42 d after planting. Root samples of four plants were collected by passing the hill soil (top 20 cm) through a 2-mm sieve. Roots were collected and washed immediately. Collected root samples were stored and processed as described above.

To assess the N recovery at harvest, four plants were collected at the middle of the plots. Above-ground plant material was cut at soil surface and tubers were harvested. Plant material was processed as described above. Tubers were washed, cut in slices, dried, weighed and processed for C and N analyses as described above. Plot yields were assessed by collecting 5.3 m^2 with a two row potato plot harvester. Tubers were collected and weighed on site.

Rate of N uptake: Equation 2 was used to assess the effects of root morphological parameters on RNU. For the GS1, the RNU on a r_{sa} basis was calculated with equation 2 as:

$$RNU = [(N\text{ uptake shoot 15 d} - N\text{ uptake shoot 0 d})/\ r_{sa}\text{ at 15 d}]. \qquad \text{eq. 2}$$

The same formula was used for the RNU on a time basis but the time period of 15 d was substituted for r_{sa}. The same procedure was done for the GS2 RNU without subtracting any background N. It was assumed that most of the N in the above-ground compartment by 67 days is absorbed from the soil environment and not from the mother tuber.

Rate of N and C flux: For the field study, equation 3 was used to express the C content in the tuber at harvest as the flux of C over the above-ground dry weight at harvest. The N tuber content at harvest was defined as the N_{flux} with equation 4.

$$C_{flux} = [(\text{C tuber content at harvest})/\ \text{above-ground dry biomass at harvest}] \qquad \text{eq. 3}$$

$$N_{flux} = [(\text{N tuber content at harvest})/\ r_{sa}\text{ at 42 d}]. \qquad \text{eq. 4}$$

RESULTS and DISCUSSION

Above-ground biomass and N content: Although for GS1 there were no initial significant difference in shoot dry weights and N content at germination, 15 d after germination the above-ground dry biomass and N content was higher for Nugget than for Norkota-line 8 (P<0.05; Table I.2). The same response in above-ground dry biomass and N content was found with GS2. Above-ground dry biomass and N and C content were higher for Nugget than the Norkota-line 8 before tuber initiation at 67 d after planting (P<0.05; Table I.2). This higher C content in the above-ground biomass at 67 d contributed to a higher C/N ratio (26) for Nugget than the C/N ratio (22) observed for Norkota-line 8 (P< 0.05). These studies clearly show that Nugget is fixing higher atmospheric CO_2-C in the above-ground biomass than Norkota-line 8 (Table I.2).

Even though the Nugget variety had higher above-ground biomass and higher root surface area for both studies, tuber yields were higher with the smaller above-ground biomass producer, Norkota-line 8 (Tables I.2, I.3, and I.5). For GS2, the Norkota-line 8 tuber yield of 2320 g per plant^{-1} was higher than the 1550 g per plant^{-1} observed for Nugget (P<0.05). On a dry weight basis the Norkota-line 8 dry weight of 518 g plant^{-1} was also higher than the 377 g per plant^{-1} observed for the Nugget (P < 0.05). Our results of higher tuber yields with the smaller plant canopy of Norkota-line 8 (than those observed for Nugget) agree with the Tabook's (1999) field studies. These data show that although Nugget was a more efficient variety in producing larger roots and above-ground biomass, Norkota-line 8, variety with smaller canopy and rooting systems, was more efficient in producing tubers.

Our third study found similar responses in above-ground and tuber yield differences among varieties compared to our two greenhouse studies. The total N uptake was not significantly different among varieties and was estimated at 192 and 185 kg N ha^{-1} for Norkota-line 8 and Nugget respectively. The N budget for this field study was 90 kg N ha^{-1} applied at preplant, 45 kg N ha^{-1} applied with six fertigations, about 35 kg N with irrigation water, 10 kg N ha^{-1} initially in the root zone, and an estimated release of 30 kg N ha^{-1} from crop residue, and SOM mineralization for a total budget of 209 kg N ha^{-1}. The total N uptake by above-ground plants and tuber for the field study was estimated with equation 5 to be about 92% for Norkota-line 8 and 89% for Nugget.

$$\text{Total N uptake \%} = ((\text{crop N uptake/N available in the system})*100) \qquad \text{eq. 5}$$

There were no large precipitation events during the year and the water was carefully managed to replenish the water lost from the root zone. This study is in agreement with other researchers who have reported that there is potential to keep NO_3-N leaching losses below the root zone in irrigated sandy soils to a minimum with proper BMPs (Smika et al., 1977; Hergert, 1986; Westerman et al., 1988; Schepers et al., 1995; Thompson and Doerge, 1996*a,b*). This study, agrees with results from Westerman et al. (1988) that reported high NUE of the applied N fertilizer.

These results were also in agreement with the Tabook's (1999) field studies that also reported higher above-ground biomass and N uptake by Nugget, but lower tuber yields. The tuber N content data is also in agreement with other researchers who found that about 20% of the total N content at harvest was in the tuber compartment. (Lauer, 1984;

Roberts, et al., 1991).

Root properties: For GS1 the underground root morphological parameters had a similar response to those observed by the above-ground compartment. Although there were no significant initial differences at time zero, 15 d after germination Nugget had higher root length and surface area than Norkota-line 8 ($P<0.05$; Table I.3). The second greenhouse study also found similar root morphological responses. Before tuber initiation at 67 d Nugget had a higher root length and surface area than Norkota-line 8 ($P<.05$; Table I.3).

The field study found similar responses to those observed with GS1 and GS2. The root length and surface area at 42 d after planting was higher for Nugget than for Norkota-line 8 ($P < 0.05$; Table I.6).

Effect of N fertilizer additions Application of N fertilizer increased above-ground potato dry biomass, N uptake and C fixation and sequestration by the above-ground compartment ($P < 0.05$; Table I.2). The 240 kg N ha^{-1} N fertilizer rate increased the above-ground N content that contributed to an above-ground C/N ratio of 23, lower than the C/N ratio of 26 observed for the 160 kg N ha^{-1} rate ($P < 0.05$). The root morphological parameters also responded to higher N fertilizer application rate with larger root length and surface area observed for the equivalent 240 kg N ha^{-1} ($P<.05$; Table I.3).

The 160 and 240 kg N ha^{-1} treatments received an equivalent application of 3 and 4.5 g N can^{-1}, respectively. Additionally, there was 1.1 g of N initially as NO_3-N. Since a sandy loam soil with a low soil organic matter (SOM) content was used and distilled water with minimum or zero N content, it is expect that the added N fertilizer and initial inorganic N were the main N sources for the potato uptake measured at 67 d after planting for GS2. The recovery of N calculated with equation 6 was about 70% for both N fertilizer treatments. These data agree with results from Westermann et al. (1988) and Tabook (1999) who showed that we can expect significantly higher N recoveries with potato, given that N losses out of the root zone are kept to a minimum.

$$\text{Recovery of N} = [\text{N content in plant} \div (\text{Initial soil N} + \text{added N fertilizer}) * 100] \quad \text{eq. 6}$$

The addition of N fertilizer significantly increased the tuber yield. The higher N rate fertilizer equivalent to 240 kg N ha^{-1} had higher tuber yield of 2320 g $plant^{-1}$ than the 1550 g $plant^{-1}$ observed for the 160 kg N ha^{-1}.

Rate of N and C uptake: Table I.4 shows that when expressed on a time basis for both studies at 15 and 67 d, Nugget had a higher RNU. If we account for the root morphological properties, assuming a uniform N uptake across the root (Cushman and Barber, 1981), the RNU is higher for the Norkota-line 8 than for the Nugget ($P<0.05$ Table I.4). These data show that for the Nugget variety that had a lower RNU per surface area, the root morphological parameter such as larger root surface area is the key for increasing NUE. For Norkota-line 8, a variety with smaller root surface area, the higher N influx rate on a surface area basis is of more importance for increasing NUE. This study suggest the hypothesis that for potato varieties with larger root surface biomass the morphological parameters such as larger root surface area are more important for increasing NUE. The data also suggest that the root physiological parameters that control a higher rate of N uptake are more important for potato varieties with smaller root surface area.

Although, addition of N fertilizer increased the total N uptake, the rate of N uptake on a root surface basis was lower with the higher N fertilizer rate. Since it was observed that at higher N fertilizer applications the root surface area and C content increased for both varieties while RNU decreased, it was also proposed the hypothesis suggesting that potato has a physiological mechanism that correlates a higher C sequestration rate by the root and larger surface area at a given stage of crop development (similar environmental conditions) with a lower RNU on surface area basis. This effect observed for the change in rate of N uptake from the 160 to 240 kg N ha^{-1}, may also explain the observed differences in rate of N uptake on a surface area basis among varieties (larger *vs* smaller rooting systems). Since we are using the same time period and environmental conditions to compare the effect of N fertilizer rate and varieties on RNU, we suggest that as root C sequestration increases root growth (and above-ground growth), RNU on a root surface area basis is reduced. Another hypothesis is that the root variety is expending higher energy and resources in growing than in the uptake and translocation of N to the above-ground biomass or tubers.

Assessment of N and C flux: It is clear from our two greenhouse studies that the rates of N uptake at 15 and 67 d were higher for the root surface area of Norkota-line 8 (Table I.4). To conduct an assessment of the C and N flux to the harvested tubers, the net C flux to the tubers will be expressed as the C content in the tuber at harvest on an above-ground dry weight basis also at harvest. The rate of C flux into the tubers was significantly higher for the Norkota-line 8 variety even though this variety had much smaller dry biomass production in the above-ground plant.

The net N flux to the tubers was also expressed as the N content of the tubers at harvest on a root surface area (root surface area at 42 d) (Table I.7). The N flux to the tubers for Norkota-line 8 was higher than for Nugget. These net higher C and N fluxes to the tubers suggest that the smaller size Norkota-line 8 variety was fixing, transporting and sequestering C in the tubers faster than the Nugget. It also suggest that N was transported faster to the tubers with Norkota-line 8. Norkota-line 8 variety appears to be more efficient in generating higher tuber yields than the Nugget variety that uses some of its energy and C in growing larger above-ground and root biomass compartments. Apparently, under BMPs that minimize N losses, the Norkota-line 8 variety with shallower rooting systems and smaller above-ground biomass is a more efficient variety that can produce higher tuber yields. Equation 7 was used to calculated the Nutrient Efficiency Ratio (NER) as described by Gerloff and Gabelman (1983). The NER of 277 for Norkota was higher than the 247 for Nugget ($P < 0.05$). The Norkota was more efficient in using a unit of N to produce a unit of yield.

$$\text{NER} = (\text{units of yields, g})/(\text{total unit of element in tissue, g}) \qquad \text{eq. 7}$$

CONCLUSION

These studies are in agreement with other research that show that under conditions of minimum N losses, BMPs can increase NUE and recovery of N with potatoes. We found that under BMPs that minimize N losses, there were no differences in NUE between Norkota-line 8 and Nugget. Although the Norkota variety had a smaller rooting system, this variety had a higher rate of N uptake on a root surface area basis than the Nugget. Although the Norkota-line 8 variety had smaller above-ground biomass and root surface area the C flux through the above-ground plant biomass to the tubers was faster. We suggest that this higher C and N flux into the tubers contributed to the higher tuber yields observed for Norkota-line 8. The studies suggest that under BMPs that minimize N losses Norkota-line 8 is a more efficient nutrient-use variety with potential for higher yields. Additional studies are needed to further investigate the effect of root and morphological parameters under different soil and environmental conditions such as excessive irrigation, salinity, interactions with other nutrients, other soil types and different combinations of N timing fertilizer applications. This study suggests that both root morphological and physiological parameters are important in increasing NUE and their interactions with higher yields and product quality should be investigated.

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Table I.1. Soil chemical properties for soil used in greenhouse studies.

pH	EC	Soil Organic Matter	NO_3-N	P	K	Zn	Fe	Mn	Cu
	dS m^{-1}	%	------------------------			mg kg-1			------------------------
6.9	0.35	0.7	6.4	9.3	213	0.9	7.3	2.1	1.3

Table I.2. Shoot dry weight, nitrogen (N) and carbon (C) content per plant for Nugget and Norkota-Line 8 varieties grown in greenhouse. For greenhouse study one (GS1) potato seed was germinated in the laboratory and transplanted to greenhouse pots and grown for 15 days†. For greenhouse study two (GS2) potato seed was planted directly in greenhouse pots and grown under two different N rates equivalent to 160 and 240 kg N ha^{-1} on a weight basis.¥

Study	time days	Variety/ N-Rate	Shoot dry weight	N	C
			----------	g ----------	----------
GS1	0	Nugget	0.6 a	0.04 a	NA†
		Norkota	0.6 a	0.03 a	NA†
GS1	15	Nugget	6.1 a	0.32 a	NA†
		Norkota	5.2 b	0.27 b	NA†
GS2	67	Nugget	230 a	3.70 a	96.1 a
		Norkota	173 b	3.30 b	72.9 b
		160	185 b	3.0 b	76.8 b
		240	217 a	4.0 a	92.3 a

¥ Data within a column and variety/N rate with different letters are significantly different at $P < 0.05$

NA† Not available

Table I.3. Root dry weight, length, average diameter, and surface area per plant for Nugget and Norkota-Line 8 varieties grown in greenhouse. For greenhouse study one (GS1) potato seeds were germinated in the laboratory and transplanted to greenhouse pots and grown for 15 days. For greenhouse study two (GS2) potato seed was planted directly in greenhouse pots under two different N rates equivalent to 160 and 240 kg N ha^{-1} on a weight basis.[¥]

Study	time days	Variety/ N-Rate	DW (g)	Length m	Diameter mm	Surface area m^2
GS1	0	Nugget	0.1 a	12.8 a	0.16 a	0.002 a
		Norkota	0.1 a	14.0 a	0.15 a	0.002 a
GS1	15	Nugget	1.6 a	104 a	0.20 a	0.019 a
		Norkota	1.4 a	76 b	0.20 a	0.016 b
GS2	67	Nugget	9.8 a	327 a	0.44 a	0.15 a
		Norkota	6.9 b	253 b	0.48 a	0.12 b
		160	7.2 b	254 b	0.44 a	0.12 b
		240	9.6 a	325 a	o.48 a	0.16 a

¥ Data within a column and variety/N rate with different letters are significantly different at P< 0.05

Table I.4. Nitrogen rate of uptake (NRU) expressed on a time and root surface area basis for Nugget and Norkota-Line 8 varieties grown in greenhouse. For greenhouse study one (GS1) potato seeds was germinated in the laboratory and transplanted to greenhouse pots and grown for 15 days. For study greenhouse two (GS2) potato seed was planted in greenhouse pots under two different N rates equivalent to 160 and 240 kg N ha^{-1} on a weight basis.[¥]

			------------------- NRU	---------------
----- Study Area	time	Variety/	Time	Root Surface
mm^{-2}	days	N-Rate	ng N sec^{-1}	μg N
GS-1	15	Nugget	247 a	14.7 a
		Norkota	208 b	15.0 a
GS-2	67	Nugget	639 a	24.7 b
		Norkota	570 b	27.5 a
		160	518 b	25.0 a
		240	691 a	25.0 a

¥ Data within a column and variety/N rate with different letters are significantly different at P< 0.05

Table I.5. Nitrogen and C content and respectively dry weights (DW) for different plant compartments for Nugget and Norkota-Line 8 varieties grown in a field study conducted at the Colorado State University San Luis Valley Research Center, Center, Colorado. Presented data including tuber fresh weight (FW) is the mean of four collected plants per plot.

Variety	total N	total C	Shoot			Tuber			
			DW	N	C	FW†	DW	N	C
	g								
Nugget	4.8 a	134 a	75 a	1.6 a	29 a	1180 b	273 b	3.3 b	112 b
Norkota	5.1 a	140 a	47 b	1.0 b	15 b	1410 a	302 a	4.2 a	124 a

¥ Data within a column and variety/N rate with different letters are significantly different at $P< 0.05$

† Yield (FW) was also measured at 41 t ha^{-1} for Nugget (1078 g per plant) and 56 t ha^{-1} for Norkota (1472 g per plant) by harvesting 5.3 m^2 with a two row harvester,

Table I.6. Root dry weight (DW), length, average diameter and surface area per plant for the Nugget and Norkota-Line 8 at 42 days after planting in a field study conducted at the Colorado State University San Luis Valley Research Center, Center, Colorado. ¥

Variety	DW (g)	Length m	Diameter m (10^{-3})	Surface area m^2
Nugget	7.3 a	39.2 a	0.61 a	0.025 a
Norkota	4.1 b	24.1 b	0.62 a	0.014 b

¥ Data within a column and variety/N rate with different letters are significantly different at $P< 0.05$

Table I.7. Assessment of average C and N flows into Nugget and Norkota tubers at harvest. Rate of C tuber flux at harvest was expressed as total tuber C content at harvest / aboveground dry matter content at harvest. Rate of tuber N flux at harvest was expressed as the total N tuber content at harvest / root surface area measured at 42 days.[¥]

Variety	C flux g C tuber / g aboveground dry weight	N flux μg N mm^{-2}
Nugget	1.5 b	132 b
Norkota	2.6 a	300 a

¥ Data within a column and variety/N rate with different letters are significantly different at $P < 0.05$

CHAPTER II

Effect of Potato-Grain Rotations on Physical and Chemical Properties of Sandy Soils[2]

ABSTRACT

The potential for wind erosion in South Central Colorado is greatest in the spring, especially after harvesting of crops such as potato (*Solanum tuberosum* L.) that leave small amounts of crop residue in the surface after harvest. Therefore, it is important to implement Best Management Practices (BMPs) that reduce potential wind erosion, and it is important that we understand how cropping systems are impacting soil physical and chemical properties. An assessment of the effects of cropping systems in soil physical and chemical properties of coarse sandy soils was conducted to study the impact of incorporation of small grain in a potato - grain rotation. An uncultivated rangeland site and three fields that two decades ago were converted from rangeland into cultivated center-pivot-irrigation-sprinkler fields were sampled. Plant and soil samples were collected in the rangeland area and the three adjacent cultivated sites. The soil at these sites was classified as a Gunbarrel loamy sand (Mixed, frigid Typic Psammaquent). We found that for the rangeland site the brush species is contributing to C sequestration and increases in soil organic matter (SOM) while the bare soil areas of the rangeland are losing significant amounts of fine particles, nutrients and SOM. Mean crop C residue returned to the soil reduced wind erosion and was also correlated with the percentage of silt and clay (r^2=0.99; P < 0.01). Crop residue returned to the soil was also positively correlated with the SOM-C (r^2=0.99; P < 0.01) and

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[2] **Chapter submitted for Journal Publication**

SOM-N content (r^2=0.99; $P < 0.01$). When we added about 2.5 t C ha^{-1} y^{-1} with the small grain crop residue we increased the level of SOM for these coarse sandy soils. For CS2 we added about 2.1 t C ha^{-1} y^{-1} that contributed to maintain the SOM C levels. Small grains have the potential to contribute to the conservation of SOC and/or sequester C for these rangeland systems that have very low C content and that are also losing C from their bare soils areas (40%). Cultivation of these rangelands can potentially contribute to C sequestration in the SOM. There is potential to use cropping systems and varieties as universal tools to increase recoveries of N and conserve water quality by sequestering N in the soil organic matter, thereby reducing N losses to the environment, reducing erosion and increasing agricultural sustainability.

ABBREVIATIONS

BMPs, Best management practices

CMIN-C, Carbon associated with the mineral fraction

CMIN-N, Nitrogen associated with the mineral fraction

MBC, Microbial biomass carbon

MBN, Microbial biomass nitrogen

POM, Particulate organic matter

SOC, Soil organic carbon

SOM, Soil organic matter

SON, Soil organic nitrogen

INTRODUCTION

It has been reported that with continue population growth and increasing demands for natural resources the reduction of erosion and the development of a sustainable intensive agriculture is a priority during the new millennium (Pimentel et al., 1995; Lal, 1995 & 2000). Since most of the world's arable land is already under cultivation (Baligar et al., 2001), we need to continue the development of best management practices that maximize yields while increasing agricultural sustainability (Lal, 2000; Baligar et al., 2001; Berry et al., 2003). Our goal was to conduct an assessment of the effects of potato small grain rotations in physical and chemical soil properties of cultivated rangeland.

Rangeland soil chemical properties such as SOC, total N and nutrient concentrations can be variable and can be correlated to plant species. This variability in distribution of resources was named "island of fertility" or resource islands (Bolton et al., 1990 & 1993; Halvorson et al., 1992). Smith et al. (1994) reported that microbial biomass C (MBC), microbial biomass N (MBN), and mineralization were correlated with vegetative cover of semi-arid shrub-steppe ecosystem. They found that the mineralization of C and concentrations of microbial biomass was spatially correlated to the brush area, but not near the area of grass species. Halvorson et al. (1992) reported that measurements of nutrients taken randomly may not be independent and that these spatial patterns should be taken into consideration when sampling these systems.

It is important to sample brush, grasses, and bare soil areas when evaluating semiarid rangelands to account for this soil variability. Although assessment of brush areas is intensive and labor and time consuming, previously developed techniques can be used to help facilitate the task. Plant biomass production from brush areas have been correlated using dimension and regression analyses of vegetative properties such as stem and crown diameter, crown volume and height by circumferences (Whittaker, 1966 & 1970; Newbould, 1967; Rutherford, 1979; Bentley et al., 1970; Bartolome and Kosco, 1982; Murray and Jacobson, 1982; Vora 1988; Hughes et al., 1987).

The dynamic of seasonal changes reported by Barth and Klemmedson (1986) clearly show the importance of assessing the whole system when evaluating C and N pools of uncultivated rangeland systems. Barth and Klemmedson (1986) reported that the changes in amount of N content in the above-ground compartment of a semi-arid shrub-steppe ecosystem was correlated with soil N availability due to higher mineralization in wetter years. They also reported that higher above-ground C and N content was correlated to a spring flush growth and lower contents during winter were correlated to winter plant dormancy. Although these seasonal changes were reported, standing vegetation did not change significantly during the three year study with only a 3% increase in the above-ground, under ground, and litter compartments.

Below-ground plant parts are a significant compartment for C and N. Redente et al. (1989) reported that approximately 92% of the fixed C in a native shortgrass site of Wyoming was allocated in the below-ground compartment compared to 85% at the wheatgrass site. Schimel et al. (1985) reported that, for a catena summit, above-ground biomass for forbs and grasses were 702 and 1270 kg C ha^{-1}, while roots and detritius roots were 19200 kg C ha^{-1}. Nitrogen followed similar distribution with 21.7 kg N ha^{-1} in above-ground biomass and 364 kg N ha^{-1} in the root and detrious root compartment. The SOC and SON for the top 30 cm were 16950 kg C ha^{-1} and 2320 kg N ha^{-1}, respectively.

Schimel et al. (1985) found that the mid slope and footslope sites had similar trends for organic C and N, SOM > underground plant compartment > above-ground compartment.

Carbon pools have been described by Follett et al. (2000) who explained the important role of soils in the Global C cycle. The SOC pool has twice the atmospheric CO_2-C pool and 4.5 times the C-pool in land plants. Parton et al. (1987) considered dynamics and residence time when dividing the SOC pool. The larger carbon pool with longer turnover rates of 200 to 1500 years, was named the recalcitrant C pool. The slower pool with turnover rates of 20 to 40 years was called the physically protected pool. The faster and active pool with turnovers rates of 1 to 5 years was described as a pool composed of mainly live microbes, microbial products and SOM. Parton et al. (1987) used these dynamics and residence time compartmentalization to develop and calibrate the CENTURY model that can be used to evaluate management practices on SOC.

Cambardella and Elliott (1992) developed a method to measure the compartmentalization of the SOC in particulate organic matter (POM) and carbon associated with the mineral fraction (CMIN-C). They found that the organic C % in the POM for bare fallow, stubble mulch, no-till and the native sod were 18, 19, 25 and 39% respectively. Cambardella and Elliott (1992) showed that cultivation will reduce the C in the POM fraction. They reported that this POM simulated the slower pool described by Parton et al. (1987). Hussain et al. (1999) reported that carbon was higher in the POM and mineral associated fractions in the non-tillage systems because of the lower decomposition rates. Clay content has been positively correlated with the protection of SOM from microbial mineralization (Paul and Van Veen, 1978; Van Veen and Paul, 1981; Parton et al., 1987; Spain, 1990). Additionally, soil aggregates and structure have been correlated with SOC and soil microbial biomass (Tisdall and Oates, 1982; Ross et al., 1982). Tillage can expose protected SOM and increase the rate of decomposition contributing to decreased SOM and SOC levels (Hass et al., 1957; McGill et al., 1981; Tiessen et al., 1982; Odell et al., 1984; Dalal and Mayer, 1986; Havlin et al., 1990).

Minimum tillage systems have high accumulation of surface crop residue that can contribute to increased SOC and sequestered atmospheric C (Havlin et al., 1990; Karlen et al., 1994; Hunt et al., 1996; Salinas-Garcia et al., 1997; Hussain et al., 1999). Paustian et al. (1997) discussed the management controls and practices that affect SOC. They described how cultivation increased SOC losses from the native site. There is an initial rapid loss then a decline until SOC is stabilized after several years. They reported that if C inputs to soil system can be increased to those of native systems, with intensive irrigation, productive varieties, and higher N inputs, SOC can potentially be restored to previous or higher levels under no till-management.

Hussain et al. (1999) reported that non-tillage systems with less erosion had higher Ca, Mg, and P in the surface soil than plowed systems. They also found that K content was lower in the non-tillage system than the plowed system due to K leaching from the profile in the non-tillage systems. Black and Tanaka (1997) reported that in order to maintain or increase soil productivity in the Great Plains, water and wind erosion will need to be controlled and that minimum and no-till systems appeared to increase SOC and SON when compared to conventional tillage systems.

Erosion impacts can contribute to the removal of soil particles, SOM, and nutrients reducing soil productivity (Lal, 2000; Campbell and Zentner, 1993). Rotations with small grains and winter cover crops can reduce potential wind erosion. Covering the soil or using high residue crops significantly reduces erosion potential (Bilbro, 1991; Campbell and Zentner, 1993; Delgado et al., 1999).

Cropping systems and amount of crop residue returned to the soil have been correlated to SOM levels. When compared to fallow systems, increasing cropping intensity has been found to increase the amount of crop residue returned to the soil increasing the amount of SOC and SON (Rasmussen and Rohde, 1988; Peterson and Westfall, 1997; Black and Tanaka, 1997; Bowman et al., 1999; Halvorson et al., 1999; Sherrod et al., 2003) and P (Bowman and Halvorson, 1997). Bowman et al. (1999) reported that total SOC and SON for continuous cropping rotations increased by 20% when compared to wheat-fallow. The POM-C doubled with intensive cropping system, while POM-N and soluble organic carbon increased by 1/3 for the top 5 cm.

Larson et al. (1972, 1978) and Rasmussen et al. (1980) have reported that returning crop residue to the soil can contribute to maintain SOM. Campbell and Zentner (1993) reported that the SOC correlated to the C inputs into the system. Havlin et al. (1990) found that increases in the amount of crop residue returned to the soil increased the amount of SOC and SON. The increases were higher with no till than conventional tillage, but conventional tillage still increased the amount of SOC and SON correlated with the amount of crop residue returned into the soil. Larson et al. (1972) reported that additions of 16 Mg crop residue ha^{-1} y^{-1} increased SOC by 47%. They reported that the amount of corn (*Zea mays* L) stalk or alfalfa (*Medicago sativa* L.) residue to be added to the soil to maintain the SOC levels was 6 Mg ha^{-1} y^{-1} for a silty clay loam (Typic Hapludoll).

Havlin et al. (1990) reported that crop rotations will have an impact on SOC and SON increasing SOC and SON from continuous soybeans (*Glycine max* L.), to soybeans-sorghum (*Sorghum bicolor* L. Moench), to higher increases with continuous sorghum. Kuo et al. (1997) studied the effect of several winter cover crops on SOC and found that rye and ryegrass were the better tools for increasing SOC than winter pea (*Lathyrus hirsutus* L.), hairy vetch (*Vicia villosa* Roth), and canola (*Brassica napus* L.). Similarly Christenson (1997) reported grain crops such as corn with higher C/N ratios contributed to higher increases in SOC. They reported that after 19 years of cultivation of a silty clay loam (Mollic Haplequept) the four-corn-sugarbeet (*Beta vulgaris* L.) rotation (C-C-C-C-SB) was 16.1 g C kg soil^{-1}, not significantly different from the initial 16.4 g C kg soil^{-1}. The SOC in the corn-sugarbeet system was lowered to 15.6 g C kg soil^{-1}. The SOC in the Navy bean (*Phaseolus vulgaris* L.) – Sugarbeet rotation was the lowest with 14.1 g C kg soil^{-1}. These changes in SOC were correlated with crop residue inputs that were higher for the C-C-C-C-SB (270 Mg C ha^{-1}), the C-SB with 208 Mg C ha^{-1} and the Navy bean – SB with 103 Mg C ha^{-1}. Similar tendencies were observed with the SON. They concluded that SOC and SON declined for all systems. However, where corn was grown over 50% of the time the declines were lower. Using $^{13}C/^{12}C$ carbon isotope analysis Follett et al. (1997) found that about 5.4% of the wheat small-grain crop residue that was returned over 84 years of wheat-fallow systems at Akron, Colorado was incorporated into the SOC, higher than the 10.5% that was incorporated during 20 years of cultivation at Sidney, NE. Follett et al. (1997) reported that about 18 kg of C plant residue ha^{-1} was needed to sequester 1 kg of C ha^{-1} in the SOC at Akron, Colorado, almost twice the 10 kg ha^{-1} needed at Sidney Nebraska. Follett et al. (1997) studies showed that tillage reduced SOC sod > native > plowed systems. These isotope techniques can also be used to identify and trace the fate of C in the POM and C associated with the mineral fraction (CMIN-C) (Six et al., 1999). Six et al. (1999) suggested that there is a faster turnover rate of macro-aggregates from conventional tillage compared to unconventional tillage which contributes to a lesser stabilization of new SOM in micro-aggregates. Campbell et al. (1991*a,b*) reported that soils with high organic matter are more likely to show greater decreases in SOM and more difficult to maintain or increase their SOM levels.

Nitrogen inputs (N fertilizer) contributes to higher yields, higher crop residue returned to the soil contributing to higher SOC and SON (Campbell and Zentner, 1993; Rasmussen et al., 1980; Janzen 1987; Glendining and Powlson, 1991; Campbell et al., 1991b; Havlin et al., 1990). Larson et al. (1972) reported that additions of crop residue at a rate of 16 Mg ha^{-1} y^{-1} increased C, N, S, and P in the soil by 47, 37, 45 and 14%. They also found that exchangeable K increased with the amount of residue added to the soil for this silty clay loam. Havlin et al. (1990) reported that N fertilizer increased SOC and SON in the soil profile.

Residue Mineralization can be affected by several factors that can control the rate of C mineralization (Stevenson, 1982), among them the C/N ratios that can be used to assess the mineralization of N. Crop residue with C/N ratios greater than 35 have higher N immobilization (Pink et al., 1945 & 1948). In some instances with the initial mineralization of the crop residue the soil N is immobilized (Mitchell and Teel, 1977; Frye et al., 1985; Holderbaum et al., 1990; Doran and Smith, 1991; Decker et al., 1994). Doran and Smith (1991) used this relationship to report that crop residues with C/N ratios lower than 20 have a greater N fertilizer equivalency. Similar relationships have been reported for other nutrients such as P and S. The P and S ratios where immobilization occurs are 300 and 400, respectively (Fuller et al., 1956; Stevenson, 1982) while release of P or S was reported at ratios of 200. It has been reported that for K, Ca, and Mg the major factor controlling the supply to plants is the relationship between exchangeable and soluble forms of these ions. Cyling of crop residues can play a significant role in nutrient's availability (Mengel and Kirby, 1982; Rebafka et al., 1994; Whitbread et al., 1999; Sahrawat, 2000; Fageria and Baligar, 2001; Castellanos et al., 2001; Delgado and Follett, 2002).

Delgado et al. (1996) used the Cambardella and Elliott (1992) POM method to study N cycling on long term ^{15}N studies in a catena of the shortgrass steppe. Delgado et al. (1996) results were in agreement with the CENTURY model, compartmentalization of the soil organic N (SON) based on the residence time and cycling. Delgado et al. (1996) found that the active pool of microbial biomass and ^{15}N cycling from easily decomposable plant materials were the primary source of N for plant uptake in the shortgrass steppe.

Microbial biomass C was reported to be 4.3, 2.8, and 2.2 % of the SOC for grass pasture, annual cropping and wheat and fallow systems while microbial biomass N was 5.3, 4.9 and 3.3%, respectively (Collins et al., 1992). They found that the amount of microbial biomass will be seasonally dependent and that it was higher in the spring. Annual cropping significantly reduced the amount of microbial biomass and SOM. Follett and Schimel (1989) reported that increasing tillage reduced the capability of the soil systems to immobilize mineral N. They found that the higher microbial biomass C and N was at the native grassland, which was higher than both non-tilled and plowed systems.

MATERIAL AND METHODS

Study area: These studies were conducted in a high altitude intermountain desert valley of South Central Colorado with an average elevation of 2348 m and annual precipitation of 168 mm (USDA-SCS, 1973; Edelmann and Buckles, 1984). To evaluate the impact of cropping systems on disturbed rangeland we sampled a rangeland area and three cultivated sites, with similar agricultural practices. These three sites were converted from rangeland into cultivated center-pivot-irrigation-sprinkler fields two decades ago. The main variability in crop management at these sites has been the amount of straw returned into the surface soil. The USDA-NRCS personnel identified the soils at these sites as a Gunbarrel loamy sand (Mixed, frigid Typic Psammaquent) that is representative of most of the main type of soils in this region that are of a coarse sandy texture over a coarse textured substratum. They also identified the crop history at the cultivated sites through interviews with farmers.

Plant biomass sampling: Plant samples were collected in the cultivated areas and in the adjacent rangeland site. The rangeland plant species were black greasewood (*Sarcobatus verniculatus*), alkali sacatone grass (*Sporobulus airoides* Torr.) and bare soils areas with small Kochia (*Scoparia (L.) Schrad*) annuals. Plant density covered by greasewood brush was determined by sampling six random 16 m^2 areas. Each plot was marked with a rope and stakes and plant biomass production from brush areas was determined using dimension and regression analyses of vegetative properties such as stem and crown diameter, crown volume and height by circumferences (Table II.1) (Whittaker, 1966, 1970; Newbould, 1967, Rutherford 1979; Bentley et al., 1970; Bartolome and

Kosco, 1982; Murray and Jacobson, 1982; Vora 1988; Hughes et al., 1987). Plant diameters were measured by using the longest length, then measuring at 90 degrees the opposite diameter. The height was also measured for each plant. We sampled four large, four medium and four small sized plants. Surface litter was collected under the brush. Above-ground plant material that was cut at the soil surface with a saw and roots were harvested from the top 0.6 m depths.

The grass covered areas were minimal and were measured with a ruler for surface area in each one of the six sampled plots. The above-ground grass biomass was determined by sampling a circle that was 20 cm i.d. Only four grass samples were collected.

The bare soil area was determined by subtracting the brush and grass areas from the total sampled area. The bare soil areas had some small annual Kochia plants and scattered litter. The surface area covered by annuals or scattered surface litter was determined using a line transect 30.5 m long, placing a frame (0.36 x 0.61 m) every 3.1 m along the transect with a hit intercept method (USDA-SCS, 1988). All plant material or surface litter in each square was collected.

Rangeland and cultivated sites were sampled within two weeks. Samples were brought to the laboratory from the field within 24 hours. Plant material was brought to the laboratory, oven dried at 55 ^{o}C for two days, ground and analyzed for total C and N content by dry combustion with an automated C-N analyzer (Carlo Erba Strumentazione, 1988). The C and N content for the plant roots, surface litter, and underground litter were corrected for soil contamination using the dry ash procedures described by Clark (1977) and Schimel et al. (1986).

Soil sampling: At random we selected four of the six plots previously used for plant biomass measurements. In each one of these four plots we selected at random a medium size brush plant and collected the soil sample at a random direction 0.3 m away from the center of the brush plant. Soil samples under the grass and bare soil areas were collected in the same direction away from the center of the brush. Soil samples were collected under greasewood, grass, and bare soil areas by driving a PVC core (20 cm i.d.) into the soil. Cores were dug out carefully to maintain the soil volume for bulk density measurements. Each soil core was sealed with plastic wrap around both end of the core and cores were kept in coolers until they were brought into the laboratory, where they were then stored in a refrigerator at 4 ^{o}C.

Cores were processed as soon as possible. Soil water content was measured immediately after taking the cores out of the refrigerator. Soils were sieved through a 2-mm mesh and a subsample was collected immediately and stored again back into the refrigerator for microbial biomass analyses. A second soil water content measurement was collected immediately after the sieving was completed. The rest of the soil sample was air-dried, picked free of roots and litter and weighed. A subsample was sent to Colorado State University Soil and Plant Laboratory Analyses for texture analyses and P, K, Cu, Mn, Fe, and Zn analyses. Additionally, another CSU analysis done was the soil water content at 0.05 MPa.

Inorganic C was determined by analyzing an initial soil sample, then treating a soil sample with 1 M H_3PO_4 acid and running a soil C analysis again. Soil C and N analyses were conducted with a Carlo-Erba analyzer as described above. For each sample two extractions were conducted by weighing 20 g of soil, extracting the soil with 100 mL of

2M KCl by shaking samples for one hour and filtering and saving the liquid fraction for chemical analysis. Extracts were run for NO_3-N and NH_4-N with colorimetric analysis by a Technicon©1 autoanalyzer (Bran-Luebbe Analyzing Technologies, Inc. 1987).

Physical fractionation of the soil SOM: Physical fractionation of soil organic matter was conducted as described by Cambardella and Elliott (1992). Ten gram subsamples (two reps) of dry soils were dispersed in 30 mL of five g L^{-1} sodium hexametaphosphate by shaking for 15 h on a reciprocal shaker. The POM was collected on a sieve (53 um) and rinsed several times with deionized water. The soil slurry passing through the sieve, containing the CMIN-C, was dried in a forced-air oven at 50 °C, weighed and ground with a mortar and pestle before the C and N were determined. The C and N were determined from the total organic C and N in the soil with equation 1 (Cambardella and Elliott, 1992).

$$\text{POM} = \text{Total Soil Organic C in the soil} - \text{CMIN-C.} \qquad \text{eq. 1}$$

Microbial Biomass: Microbial biomass analyses were conducted as described by Follett and Schimel (1989). Samples were sent to the CSU Soil Testing Laboratory for measurements of water holding capacity at 0.05 MPa. Soil samples were all placed in snap-cap vials and water content was brought to the measured water content at 0.05 MPa with deionized water. Samples were left overnight to equilibrate. Each treatment consist of two replicated 50 g soil samples. Two duplicate samples were placed in separate glass containers that were 1.89 L and were made air tight with rubber ring and screw-type lid. Each container had an alkali trap (1M NaOH) placed in to determine the CO_2 evolution. Samples were incubated in the dark at a constant temperature of 25 °C.

Alkali traps were changed and CO_2 evolution was determined at 10 and 21 d by the chloroform fumigation procedure and equations of Jenkinson and Powlson (1976) and Voroney and Paul (1984). Biomass C and N were calculated using equations 2, 3 and 4. Where C_f and N_f are the CO_2-C evolved and net NH_4-N released during 10 d incubation for the chloroform CCl_4 fumigated soil; N_{uf} is the net NH_4-N released during the same 10 d incubation for the fumigated soil. Chemical analysis in the alkali traps was determined by titration method based with HCl standards in the presence of $BaCl_2$.

$$\text{Microbial Biomass C} = C_f/0.41 \qquad \text{eq. 2}$$

$$\text{Microbial Biomass N} = (N_f\text{-}N_{uf})/K_n \qquad \text{eq. 3}$$

$$K_n = [(-0.014)(C_f/N_f) + 0.39] \qquad \text{eq. 4}$$

Crop History USDA-NRCS personnel interviewed farmers at these three sites and determined the crop history, including yields and average N fertilizer use. The mean rotation for the most intensive cropping system one (CS1) was two years of potato and one year of small grain, either wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.)(P-P-Gr). The other two systems had longer time on small grains with average Gr-Gr-P rotation for cropping system two (CS2) and Gr-Gr-Gr-Gr-P for cropping system three. All fields applied the BMPs recommended for these areas described by Ristau (1999) with the major differences being the amount of crop residue returned to the soil.

Delgado et al. (1998) data for average C and N percentage levels for plant compartments and varieties in this region had been collected across several years and farming systems. Some of the data reported by Delgado et al. (1998) used values from plant samples that were collected at CS1, CS2, and CS3. We used the mean values reported across several years by Delgado et al. (1998) to calculate the average N and C content for these cropping systems.

Crop residue for CS1 was baled and removed so the average crop residue returned to the soil reflects this transport of C off-site. For CS2 and CS3 the crop residue was incorporated to an approximate depth of 10 to 12 cm. This was done by deep chiseling the chopped small grain residue into the fields and following with a chisel plow in the Fall. Spring tillage involved chisel plowing again and then roller packing. The SAS analysis of variance GLM and LSD mean for completely randomized block design (SAS Ins., 1988) was the statistical tool used to test for difference among brush, grass, or bare soil. It was also used to determine mean values for range sites and cultivated sites following the same design.

All three cultivated sites were in potato when the soil samples were collected. Soil cores were obtained at the midslope of the hill where the tubers were planted, in the middle of July at the same time the rangeland was sampled. All soil samples were treated similarly as far as the handling, procedures and analyses done on the rangeland soils. To estimate C and N content at the above-ground plant compartments we used average yields and data from Delgado et al. (1998).

RESULTS AND DISCUNSION

Rangeland: The area covered by brush, grass, and bare soil was 59, 1, and 40%, respectively. Although we called the non-brush and non-grass areas the bare soil area, about 15% of the bare soil area was covered by annual and/or surface litter. The total rangeland area covered by vegetation (brush, grass and annuals) or surface litter was 75%. With one quarter of its surface area in bare soil and constantly exposed and unsheltered, the rangeland is susceptible to significant wind erosion which is the main mechanism for off-site transport of fine particles for these uncultivated natural systems.

Table II.2 showed that the content of C in above-ground, surface litter and below-ground plant compartments was larger in the brush area (Table II.2; $P<0.05$). Of the plant-litter C pool, the C located in the surface litter and below-ground plant compartment was 70, 63, and 91% for the brush, grass and bare soils areas, respectively (Table II.2). The lower 63% for the grassland C was because the C in the crowns was reported as part of the above-ground C since due to wind erosion some of the crowns were above the soil surface. Only roots and underground plant litter were allocated in the below-ground C compartment. For N, we found that 91, 83, and 91% of the N was compartmentalized in the below-ground plant compartments.

Soil pH was about 8.6 and did not differ between areas of brush, grass and bare soil areas (Table II.3). Bulk density was lower for the brush and grass, probably due to the effect of higher soil organic matter that can increase aggregates and porosity and can lower soil bulk density (Lal et al., 1999). Additionally, the brush and grass cover areas had lower soil erosion, conserving a higher percentage of fine particles such as silt and clay, particles that are correlated with the protection of SOM and aggregates (Paul and Van Veen, 1978; Van Veen and Paul, 1981; Tisdall and Oates, 1982; Ross et al., 1982; Parton et al., 1987; Spain, 1990).

There was a larger significant sand content in the bare soil areas with lower percentage of silt and clay, probably due to the fact that soils with over 50% uncovered and unprotected area are highly susceptible to wind erosion. We suggest that wind erosion has been the main mechanism for losses of fine particles and the reason for creating coarser soil textures in bare soil areas when compared to brush and grass covered areas (Campbell and Zentner, 1993; Lal, 1995; Black and Tanaka, 1997; Delgado et al., 1999).

Even though the brush and grass areas had lower bulk densities, they had on average a larger nutrient content than the bare soil (Table II.3). The Mn and Cu content in the grass area was higher than the bare soil. The P, Zn, Fe, and Mn in the brush areas were higher than the bare soil. The reason why the brush and grass covered areas had higher nutrients may be due to the effect of a larger rooting system that can scavenge nutrients from lower depths and deposit them in the surface layer via cycling of root and above-ground plant litter.

There was a significant correlation between the above-ground biomass and surface litter content and the below-ground C plant content (r^2=0.99; P<0.05). The higher plant above-ground biomass content was correlated with SOM-C (r^2=0.96; P<0.13) and with POM-C (r^2=0.92; P<0.10). The plant system with larger cycling potential for plant residue C had the larger SOM-C and larger POM-C content. The SOM-C, CMIN-C and POM-C were higher from the brush > grass > bare soil (Table II.4). We observed that in this non-cultivated rangeland area the areas covered by the grass were patchy and in some of these small spots erosion was removing the soil around the grass areas and exposing, in most cases, the patchy grass crowns. This may be one of the reasons of why the CMIN-C value for the grass areas was lower than the CMIN-C measured for the brush. These data show that for this rangeland site the areas covered with greasewood have larger C sequestration leading to increased soil SOM-C and POM-C content.

The microbial biomass carbon (MBC) followed the previously discussed trends with higher content from brush > grass > bare soil. Similarly the SOM-N, POM-N, CMIN-N, and MB-N mirrors the same compartmentalization of higher contents in the brush > grass > bare soil.

Cropping sequences: Cultivation and irrigation lowered soil pH by about one unit due to the increased release of H^+ from N fertilizers ($P<0.05$). Besides the application of urea-N fertilizer, the occasional application of sulfuric acid (H_2SO_4) to kill above-ground potato vines, and the application of other agrochemicals capable of lowering the pH, leaching of bases could also be contributing to the lower soil pH. On average, cultivated sites had higher surface bulk densities than rangeland. The amount of silt and clay was significantly reduced in the cultivated sites. The lower percent of fine particles in the cultivated CS1, CS2, and CS3 could be due to wind erosion that contributed to losses of fine particles and higher sand content (Delgado et al., 1999). The higher sand content may have contributed to the higher bulk densities in the cultivated sites.

Table II.5 shows that 120 Mg ha^{-1} or 6 Mg ha^{-1} y^{-1} over 20 y of fine soil particles were lost most probably due to wind erosion for CS1. The fine particle losses for the higher producing crop residue site CS3 were the lowest with about 90 Mg ha^{-1} or 4.5 Mg ha^{-1} y^{-1} over 20 y. These data suggest that the use of late-planted winter cover crops and other BMPs help to reduce potential wind erosion of fine particles as described by Delgado et al. (1999). The data show the need to continue developing BMPs to minimize potential wind erosion losses. The estimated losses in fine particles are much lower than the potential losses reported for this region by Delgado et al. (1999), but the trend agrees with their reported data.

On average the nutrient content of the cultivated sites increased ($P<0.05$; Table II.5). The content of macro and micro nutrients such as P, Zn, Fe, Mn, and Cu were higher in the cultivated sites than the rangeland. Even though there were significant losses of fine particles from the cultivated sites with potential off-site transport of SOM and nutrients, the net change in nutrient content was positive for the cultivated sites with higher macro and micro nutrient content than the rangeland. This higher macro and micro nutrient content could be a reflection of the addition of agrochemicals and fertilizers. Additionally higher yields of fertilized and irrigated systems and the use of deeper rooted crops that can scavenge nutrients from lower depths and recycle them to the surface soil layer may be reasons for higher nutrients at the cultivated site. (Delgado and Follett, 2002). In either case these areas are sequestering macro and micro nutrient in the surface soil that can potentially contribute to higher soil fertility and productivity levels.

Soil K decreased about 66% ($P<0.05$). A significant amount of this K could be attributed to K removal by the crop, wind erosion, and K leaching. Potatoes, barley or wheat can remove 140, 10, and 14 kg K ha^{-1} respectively with the tubers or grain (Delgado and Follett, 2002). If yields are increased the removal of K in the tuber compartment can increase from 140 kg K ha^{-1} to 260 kg K ha^{-1} for this region of South Central Colorado (Sparks, personal Communications). During the early years (first 10 y) there was practically no K applied to these sites. The later years (last 10 y) had regular banded low levels of K applied and occasional broadcast applications at the rate of 100 K_2O ha^{-1}. Overall, the removal by the crops were higher than the K applications; this, coupled with K losses by leaching and wind erosion, explains the significant reductions in K for these sites Although a significant amount of K may have been lost due to wind erosion, by irrigation or harvested in the grain and tubers, K was lowered at a rate of 200 kg K ha-^{1} y^{1}. The magnitude of these losses agree with Delgado and Follett (2002) who reported that most of the K is cycled back to the soil environment and is not retained in a organic compartment.

The C in the above-ground, surface litter and below-ground plant compartments for CS1, CS2, and CS3 was about 24, 38, and 32%, respectively, of the C content measured for the rangeland (Table II.6). The rangeland plant compartment serves as a larger C storage pool, especially for the hardy, wood brush plants. The rangeland plant C pool has three or four times the C in the plant compartment than that of the cultivated systems.

If we account for the average C sequestered in the grain or tuber, we still have lower C in all plant compartments at harvest for CS1, CS2, and CS3 of about 49, 64, and 56%, respectively, of the C content measured for the rangeland. To balance the C in the plant we will have to harvest and store about three years of production to have the same amount of C that was initially present in the plant C pool. The discussion of the fate of all harvested and/or transported C (two decades) is beyond the scope of this paper. How much of this harvested C in grain and tuber pools is still bound in some organic C pool after 20 years?

Above-ground crop residue increased from CS3 > CS2 > CS1 (Table II.6). The mean C crop residue returned to the soil was correlated with the SOM-C (r^2=0.99; P <

0.01) and SOM-N content (r^2=0.99; $P < 0.01$). The POM-C increased for the rotations with grain planted over 50% of the time. Crop C residue was correlated with the POM-N (r^2=0.96; $P < 0.12$). Mean crop C residue returned to the soil was also correlated with the percentage of silt and clay (r^2=0.99; $P < 0.01$) and SOM-N content (r^2=0.99; $P < 0.01$). The CMIN-C was correlated with amount of crop residue added to the system and increased with the amount of time that the systems were in small grains. Since the CMIN-C is most probably the recalcitrant C pool described by Parton et al. (1987) with larger times for turnover, this reduction in CMIN-C is probably due to wind erosion losses of fine particles and CMIN-C.

We also found that for these sandy soils some of the N fertilizer is being sequestered in the SOM. Even with higher losses of fine particles, the cropping systems that included grain in their rotations for at least 50% of the time had no changes in SOM-N or reported higher SON content. We estimated that about a net increase of 400 kg N ha^{-1} or net increase of 7 to 20 kg N ha^{-1} y^{-1} can be sequestered in the SON (or POM-N) with cropping systems that have small grains for more than 50% of their time. The small grains return crop residue with larger C/N ratios (C/N > 80) than potatoes (about C/N 20) (Delgado et al., 1998) that have a lower mineralization potential. Small grain crop residue with higher C/N ratios, less soil disturbance and lower erosion potential may be the reasons for this N accumulation. The POM-N was also increased for CS2 and CS3 (7 to 12 kg N ha^{-1} y^{-1}). These data suggest that by adding grain and incorporating the crop residue into the soils the particulate organic matter and N content is increased in the systems. This higher N content POM should contribute to increased N cycling and soil quality of these systems.

This data shows that the rotation of shallower – deeper rooted crops with higher C/N ratios helps to sequester C and N in the SOM and reduce the NO_3-N leaching losses (Delgado 1998, 2001 & Delgado et al., 1998 & 2001).

We found that the MBN and MBC were higher in the rangeland than the cultivated systems (Table II.7). This study agrees with Follett and Schimel (1989) who also reported higher MBC and MBN in the non-cultivated areas.

Larson et al. (1972) reported that about 6 Mg ha^{-1} y^{-1} of corn residue was needed to maintain the SOM. Assuming a 40% C content, we need to add about 2.4 Mg C ha^{-1} y^{-1} of high C/N grain straw residue to maintain SOM levels. Our data agrees with Larson's et. al. (1972) studies. When we added about 2.5 Mg C ha^{-1} y^{-1} with the small grain crop residue for CS3 we increased the level of SOM for these coarse sandy soils. For CS2 we added about 2.1 Mg C ha^{-1} y^{-1} that contributed to maintain the SOM C levels. The amount of C added of 1.7 Mg ha^{-1} y^{-1} of grain with CS1 was lower than those levels reported by Larson et. al. (1972) and we observed significantly larger losses of SOM C.

CONCLUSIONS

This study suggests that greasewood, the dominate species in this disturbed and uncultivated rangeland can potentially contribute to C sequestration. Greasewood areas had higher levels especially for C and N levels. These data suggest that wind erosion adds to losses of C, N, other nutrients and fine particles, and that it is also contributing to the reduction of the area covered by grass. We suggest that although the brush areas (59%) are sequestering C, the bare soil areas (40%) are losing C and fine soil particles.

Our study was designed to evaluate this site assuming that today's C, N and nutrient levels in the rangeland simulate those of two decades ago. We acknowledge that since we don't know if the rangeland system is steady state or if it is losing or gaining C and N or nutrients, our comparison may not represent how cultivation has changed the soil chemical and physical properties, when compared to non-cultivated rangeland two decades ago, but may represent how cultivation has changed the system to today's non cultivated rangelands.

There was a positive increase in C sequestration for SOM-C with CS3 (Table II.7). We observed no net changes in SOM with CS2. We found that for this potato-small grain system the SOM C was significantly correlated with the amount of crop residue that was added into the system. These results are in agreement with other scientists who found that increasing crop residue incorporation into the system increases SOM C (Larson et al., 1972 & 1978; Rasmussen, 1980; Havlin et al., 1990; Campbell and Zentner, 1993; Kuo et al., 1997; Christenson, 1997). Crop rotations with higher residue inputs can also increase SON for these potato-small grain systems. These results agree with previous findings that N fertilizer inputs can contribute to increases in N in the SOM (Campbell and Zentner, 1993;

Rasmussen et al., 1980; Janzen, 1987; Glendining and Powlson, 1991; Campbell et al., 1991b; Havlin et al., 1990).

Our study shows the importance of crop residue management for potato-small grain systems. There is potential to use crop rotations as tools to maintain the sustainability of agricultural systems, especially for systems that include shallower and low production crop residue as long as we incorporate small grain crops with high C/N ratios (Delgado et al., 1998). We could use the inclusion of small grain in these intensive-potato–small grain rotations to conserve soil quality. This universal tool (crop rotations) can be used to reduce the potential wind-erosion, losses of fine silt and clay particles, to sequester C, N and nutrients, to increase the soil fertility and productivity levels. It is well known that small grain potato rotations have on average higher yields than potato-potato rotations (Sparks, personal communications, 2003). One reason for higher yields could be the lowering of disease potential from the back to back potato rotations. This study suggests that soil quality and fertility levels can also be a potential reason for long term higher yields with a potato-small grain rotation.

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Table II.1. Relationship between area and C and N content for the above-ground litter and root compartments for brush, from South Central Colorado.[¥]

Compartment	Nutrient	Regression Equation	r^2
Above-ground	N	$y = 0.024x - 10.6$	0.98***
Litter	N	$y = 0.001x - 5.50$	0.80**
Root	N	$y = 0.001x - 1.92$	0.87**
Above-ground	C	$y = 0.078x - 340$	0.96***
Litter	C	$y = 0.023x - 135$	0.82**
Root	C	$y = 0.020x - 50.2$	0.89**

¥

Table II.2. Above-ground, surface litter and below-ground plant C and N compartmentalization for brush, grassland and bare soil of rangeland from South Central Colorado. [¥]

Compartment Soil[†]	Brush	Grass	Bare
	kg C ha^{-1}		
Above-ground	6370 a	2810 b	158 c
Surface litter	1850 a	366 b	547 b
Below-ground	13030 a	4470 b	1040 c
	kg N ha^{-1}		
Above-ground	67 a	40 b	5 c
Surface litter	70 a	30 b	20 b
Below-ground	573 a	166 b	34 c

¥ Data within a column and variety/N rate with different letters are significantly different at $P< 0.05$

† The base soil area had a soil cover area due to surface litter or annual plants of 15.0%.

Table II.3. Soil physical and chemical properties for top 0.3 m depths under brush, grassland and bare soil areas of rangeland from South Central Colorado. [¥]

Compartment	Brush	Grass	Bare Soil[†]
pH	8.6 a	8.6 a	8.7 a
Bulk density (g cm^{-3})	1.2 b	1.2 b	1.3 a
		---------- $Mg\ ha^{-1}$ ----------	
Sand	2720 b	2810 b	3090 a
Silt & Clay	586 b	694 a	611 ab
		---------- % ----------	
Silt & Clay	18 b	20 a	17 c
		---------- $kg\ ha^{-1}$ ----------	
P	64 a	38 b	30 b
K	3820 a	2920 b	3490 ab
Zn	4 a	2 b	2 b
Fe	14 a	11 b	12 b
Mn	24 a	13 b	9 c
Cu	5 b	7 a	4 b

¥ Data within a column with different letters are significantly different at $P < 0.05$

† The base soil area had a soil cover area due to surface litter or annual plants of 15.0%.

Table II.4. Compartmentalization of C and N (0-0.3 cm depth) for brush, grassland and bare soil of rangeland from South Central Colorado. [¥]

Compartment		Brush	Grass	Bare
Soil[†]				
		kg C ha^{-1}		
SOM		17600 a	14900 b	8640 c
	CMIN	12400 a	10400 b	7090 c
	POM	5250 a	3670 b	1540 c
MB		1220 a	839 b	360 c
		kg N ha^{-1}		
SOM		1770 a	1700 a	1050 b
	CMIN	1480 a	1270 a	890 b
	POM	290 ab	426 a	159 b
MB		241 a	163 b	70 c

¥ Data within a column and variety/N rate with different letters are significantly different at P< 0.05

† The base soil area had a soil cover area due to surface litter or annual plants of 15.0%.

Table II.5. Soil physical and chemical properties of non-cultivated rangeland and different cropping systems after 20 years of cultivation in South Central Colorado. Cropping systems rotations were potato-potato-grain (CS1), potato-grain-grain (CS2) and potato-grain-grain-grain-grain (CS3). ¥

Property	Range	Cropping System CS1	Cropping System CS2	Cropping System CS3
pH	8.6 a	7.4 b	7.7 b	7.4 b
Bulk density (g cm^{-3})	1.2 b	1.3 a	1.3 a	1.2 b
	$Mg\ ha^{-1}$			
Sand	2870 c	3600 a	3410 a	3140 b
Silt & Clay	597 a	477 c	503 b	506 b
	%			
Silt & Clay	17 a	12 c	13 bc	14 b
	$kg\ ha^{-1}$			
P	50 d	131 b	74 c	168 a
K	3678 a	1280 b	1300 b	1260 b
Zn	3 c	11 a	6 b	6 b
Fe	13 c	40 a	25 b	35 a
Mn	18 b	28 ab	24 b	38 a
Cu	5 b	10 a	10 a	9 a

¥ Data within a column and variety/N rate with different letters are significantly different at $P< 0.05$

† Coarse fragments by weight.

Table II.6. Carbon and N pools for microbial biomass (MB), soil organic matter (SOM), mineral fraction (CMIN), and particulate organic matter (POM) of non-cultivated rangeland and different cropping systems after 20 years of cultivation in South Central Colorado. Cropping systems rotations were potato-potato-grain (CS1), potato-grain-grain (CS2) and potato-grain-grain-grain-grain (CS3). ¥

Pool		Range	Cropping System		
			CS1	CS2	CS3
		kg C ha^{-1}			
SOM		14000 ab	9580 c	12900 b	15500a
	CMIN	10300 a	7900 b	8880 b	10800a
	POM	3770 a	1670 b	3980 a	4780a
MB		877 a	523 c	671 b	550 c
		kg N ha^{-1}			
SOM		1480 b	1080 c	1480 b	1900a
	CMIN	1250 b	949 d	1100 c	1430a
	POM	239 c	129 d	372 b	468a
MB		172 a	105 b	126 b	98b

¥ Data within a column and variety/N rate with different letters are significantly different at $P< 0.05$

Table II.7. Carbon and N pools for above-ground plant material, surface litter, harvested plant compartment (grain or tuber), and below-ground plant material (roots and or subsurface litter) of non-cultivated rangelands and different cropping systems after 20 years of cultivation in South Central Colorado. ‡Cropping systems rotations were potato-potato-grain (CS1), potato-grain-grain (CS2) and potato-grain-grain-grain-grain (CS3). ¥

Compartment	Range	---------- Cropping System ------------		
		CS1	CS2	CS3
	------	------	kg C ha^{-1} ------	------
Above-ground†	3870	1700	2160	2540
Surface litter	1320	101	96	79
Harvested†	NA	3320	3480	3300
Below-ground†	8190	1410	2810	1610
	------	------	kg N ha^{-1} ------	------
Above-ground†	42	59	40	43
Surface litter	50	3	2	2
Harvested†	NA	158	163	157
Below-ground†	355	56	100	55

¥ Data within a column and variety/N rate with different letters are significantly different at P< 0.05

† It includes the average carbon, nitrogen in standing biomass at harvest, roots or in harvested portion, respectively to the compartment.

‡ No statistical test based on farmer records