Mountain Research And Development

MOUNTAIN RESEARCH AND DEVELOPMENT, VOL. 17, NO. 3, 1997, PP. 273–282

RESPONSE OF FOUR ANDEAN CROPS TO ROTATION AND FERTILIZATION

CARLOS NIETO-CABRERA[1], C. FRANCIS[2], C. CAICEDO[3], P. F. GUTIÉRREZ[2], AND M. RIVERA[3]

ABSTRACT Crop rotation and other ancient agricultural practices have been inappropriately replaced by the use of synthetic fertilizers and pesticides. Today, it is recognized that the old traditional methods have potential for sustainable agriculture. This ongoing study (1993–1998) evaluates the effects of monocropping and crop rotation on yield, above-ground biomass, and weed populations of four Andean crops: potato (*Solanum tuberosum*), melloco (*Ullucus tuberosus*), lupine (*Lupinus mutabilis*), and quinoa (*Chenopodium quinoa*), planted both with and without fertilizer. The results of research during the first three years are presented here. Crop rotation increased marketable yields of quinoa, compared to monocropping. Potato yields followed the same trend in 1995. Lupine gave the best results as previous crop; when non-fertilized quinoa and potato were planted after non-fertilized lupine, yields were 44–188% higher than those planted as non-fertilized monocrops. Weed populations were affected only by the current season crop. Previous-season crop and previous-season fertilizer did not affect weed population dynamics. Again, lupine was the most successful current crop in maintaining lower weed populations. The first three years of the experiment indicate that lupine should be planted as the first crop in rotation systems for highland agriculture in Ecuador. Also, fertilized potato followed by non-fertilized quinoa, and melloco followed by quinoa with or without fertilization are the recommended sequences.

RÉSUMÉ *Réponse de quatre cultures andines à la rotation et à la fertilisation.* La rotation des cultures et d'autres anciennes pratiques agricoles ont été inopportunément remplacées par l'utilisation d'engrais synthétiques et de pesticides. On se rend maintenant compte que les anciennes méthodes rendaient possible une agriculture viable. Cette étude en cours (1993–1998) évalue les effets de la monoculture et de la rotation des cultures sur la biomasse au-dessus du sol et sur les peuplements de mauvaises herbes, pour quatre cultures andines, à savoir la pomme de terre (*Solanum tuberosum*), le melloco (*Ullucus tuberosus*), le lupin changeant (*Lupinus mutabilis*) et le quinoa (*Chenopodium quinoa*), plantées avec ou sans engrais. Les résultats des trois premières années de recherche sont présentées dans cet article. Par rapport à la monoculture, la rotation des cultures a augmenté la production commerciale de quinoa. La production de pommes de terre a évolué de la même manière en 1995. Le lupin changeant a donné les meilleurs résultats en tant que culture précédente ; lorsque le quinoa et la pomme de terre non fertilisés ont été plantés après le lupin non fertilisé, leurs productions respectives étaient de 44 à 188 pour cent supérieures à celles obtenues en monocultures non fertilisées. Les peuplements de mauvaises herbes n'ont été affectées que par la culture de la saison en cours. La culture et la fertilisation de la saison précédente n'ont pas affecté la dynamique des peuplements de mauvaises herbes. De nouveau, le lupin a constitué la meilleure culture de la saison du point de vue de la réduction des peuplements de mauvaises herbes. Les trois premières années de recherche indiquent que le lupin doit être planté en tant que première culture pour les systèmes de rotation de l'agriculture des hautes terres de l'Equateur. Ensuite, la pomme de terre fertilisée suivie du quinoa non fertilisé, et le melloco suivi du quinoa, avec ou sans fertilisation, constituent les séquences recommandées.

ZUSAMMENFASSUNG *Die Auswirkungen von Fruchtwechsel und Düngung auf vier landwirtschaftliche genutzte Pflanzenarten in den Anden.* Fruchtwechsel und andere althergebrachte landwirtschaftliche Praktiken wurden unangemessenerweise durch den Einsatz von synthetischen Düngern und Pestiziden ersetzt. Inzwischen wird anerkannt, daß die alten, traditionellen Methoden ein großes Potential für nachhaltige Landwirtschaft bieten. Die hier beschriebene, noch andauerende Studie (1993–1998) untersucht die Effekte von Monokultur und Fruchtwechsel mit und ohne Düngung auf Ertrag, überirdische Biomasse und Unkrautpopulationen für vier landwirtschaftlich genutzte Pflanzenarten in den Anden: Kartoffel (*Solanum tuberosum*), Melloco (*Ullucus tuberosus*), Lupine (*Lupinus mutabilis*) und Quinoa (*Chenopodium quinoa*). Es werden die Ergebnisse der ersten drei Untersuchungsjahre präsentiert. Im Vergleich mit der Monokultur verbesserte die Fruchtfolge den verkäufliechen Quinoaertrag. 1995 folgte der Kartoffelertrag dem gleichen Trend. Lupinen erwiesen sich als beste Vorgängerfrucht; auf Lupinenanbau ohne Düngung folgender Anbau von ungedüngten Kartoffeln und Quinoa ergab 44 bis 188% höhere Erträge als in düngungsloser Monokultur angebaute Kartoffeln und Quinoa. Unkrautpopulation wurden nur von der Fruchtart der jeweiligen Saison beeinflusst. Pflanzenart und Düngung in der vorangegangenen Saison hatten keinen Einfluß auf Unkrautpopulationsdynamiken. Wiederum wurde die Unkrautpopulation am erfolgreichsten von Lupinen unterdrückt. Die ersten drei Untersuchungjahre zeigen, daß Lupinen als erste Fruchtart in Fruchtwechselsystemen in der Hochlandlandwirtschaft in Ecuador eigesetzt werden sollten. Weitere ratsame Fruchtfolgen sind gedüngte Kartoffeln geflogt von ungedüngtem Quinoa sowie Melloco gefolgt von Quinoa mit oder ohne Düngung.

RESUMEN *Respuesta de Cuatro Cultivos Andinos a la Rotación con Fertilización.* La rotación de cultivos y otras prácticas culturales tradicionales fueron equivocadamente sustituidas por el uso de fertilizantes y pesticidas sintéticos. Afortunadamente, en los últimos años se está reconociendo que estas prácticas tienen potencial para ser usadas en sistemas agropecuarios autosustentables. El presente estudio fue realizado para evaluar el efecto del monocultivo y de la rotación en el rendimiento, biomasa aérea y población de malezas

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[1] Santa Catalina Experimental Station, INIAP-Ecuador. Present address: Department of Agronomy, University of Nebraska, Lincoln, Nebraska 68583-0817, U.S.A.

[2] Department of Agronomy, University of Nebraska, Lincoln.

[3] Santa Catalina Experimental Station, INIAP, Programa de Cultivos Andinos, Km 17 Panamericana Sur, P.O. Box 17-01-340, Quito, Ecuador.

de cuatro cultivos andinos: Papa (*Solanum tuberosum*), melloco (*Ullucus tuberosus*), chocho (*Lupinus mutabilis*) y quinua (*Chenopodium quinoa*), sembrados con y sin fertilizante. La investigación se está realizando en la Estación Experimental Santa Catalina en Ecuador, desde 1993 hasta 1998. Los resultados de los primeros tres años se presentan en este artículo. El monocultivo redujo los rendimientos comerciales de quinua entre 66 y 92% en 1994 y entre 15 y 64% en 1995, en comparación con las rotaciones. En papa se observó la misma tendencia en 1995. El chocho ejerció la mejor influencia como cultivo anterior. Los rendimientos de quinua y papa sin fertilización, cuando se sembraron después de chocho también sin fertilización, fueron de 44 a 188% mas altos que sus monocultivos sin fertilización. La población de malezas fue afectada solamente por el efecto del cultivo actual. Los efectos de cultivo anterior y fertilización anterior fueron no significativos para población de malezas. Nuevamente, chocho fue el mejor cultivo actual para mantener una población baja de malezas. Las parcelas de chocho en 1995 presentaron 586, 422 y 82 malezas m^2 menos que las de papa, melloco y quinua respectivamente. Después de los primeros tres años del experimento, se recomienda el uso de chocho como cultivo previo, para sistemas de rotación de cultivos en la Sierra de Ecuador. Las rotaciones de papa con fertilización seguida de quinua sin fertilización y melloco seguido de quinua, ambos con o sin fertilización, también son recomendables.

INTRODUCTION

Crop rotation is an ancient practice that consists of planting a recurrent sequence of species on the same field in successive years. It has been in common use in China and other eastern countries since about 1000 B.C. (Bullock, 1992; Karlen *et al.*, 1994). Crop rotation is used to hedge against biotic and abiotic stresses while maintaining soil fertility by erosion control; it results in decreased weed populations, reduced leaching, and increased organic matter content and available nitrogen. Crop rotation also helps to control pest populations in integrated pest management programs (Crookston *et al.*, 1988; Keller, 1989).

In the highlands of the Andean region, crop rotation was common from Pre-Columbian times until the advent of the Green Revolution (Lescano and Zeballos, 1982). Crop rotation and other agricultural practices were phased out in many developing countries under the premise that the introduction of synthetic fertilizers and pesticides would replace them (Bullock, 1992). Fortunately, this view has now changed and crop rotation and other alternatives are recognized as potentially appropriate for sustainable agriculture; these include reduced tillage, organic farming, intercropping, and agroforestry. Water use in crop rotation systems is more efficient than in monocropping systems, and since water resources are becoming a serious constraint on global agricultural production, crop rotation systems should be embraced (Ruttan, 1992).

Leguminous crops used in rotation not only increase nitrogen availability for the succeeding crop, but also improve the physical conditions of cultivated soils. For instance, soil aggregate was greater (33 %) for an alfalfa (*Medicago sativa*)–grass rotation, intermediate (24.4 %) for continuous ryegrass, and low (17.5 %) for continuous maize (*Zea mays*) (Power, 1990). An important crop used for rotation in the Andean region is lupine (*Lupinus mutabilis*) which is reported to improve N and P availability in soil (Gross, 1982). Studies involving lupine, quinoa (*Chenopodium quinua*), and potato (*Solanum tuberosum*) showed that quinoa–lupine–lupine–quinoa, quinoa–potato–lupine–quinoa, and quinoa–potato–potato–quinoa rotations gave higher yields than monocropping (Lescano and Zeballos, 1982).

A five-year study of several rotation sequences using Andean crops showed that the economic and energetic yield of quinoa–potato, quinoa–melloco, and quinoa–fava bean (*Vicia faba*) were, on average, 50% higher than either monocropping or quinoa–fallow (INIAP, 1992).

Hairy vetch (*Vicia villosa*) contributed between 110 and 119 kg N ha^{-1} to the ensuing potato crop according to Honeycutt *et al.* (1995) who also reported that the previous crop mineralizable residue N contents were highest following vetch, intermediate after lupine, and lowest after potato.

Crop rotation by itself is not sufficient to control weeds, but it is an effective complement to synthetic herbicides. For example, after 8 years of standard chemical and mechanical weed control, 1,500–3,000 weed seeds m^{-2} were found in continuous maize. In contrast, only 200–700 weed seeds m^{-2} were found in a soybean–maize rotation. In addition, densities of weed seedlings emerging before the crop were higher in continuous cropping than in crop rotations (Forcella and Lindstrom, 1988). Before the introduction of synthetic herbicides, a combination of crop rotation, smother crops, and mechanical cultivation were used to control weeds (Bullock, 1992).

Agriculture in the highlands of Ecuador is characterized by labor intensive systems with a low level of purchased inputs and an average farm size less than 5 ha. One major constraint is poor soil fertility compounded by high erosion rates. Practices such as crop rotation and weed management are of critical importance to ensure long-term sustainable production with minimal external resource use. This paper examines the effect of paired crop rotation arrangements on yield and above-ground biomass of four Andean crops: lupine, melloco (*Ullucus tuberosus*), potato, and quinoa, each with and without fertilization. It also assesses the importance of crop sequence to weed population dynamics and the energy-equivalent yield.

MATERIALS AND METHODS

The research was conducted at the Santa Catalina Experimental Station (3,050 m a.s.l.; 0° 14′ S, 78° 30′ W) of the National Institute for Agricultural Research, INIAP-Ecuador (Figure 1). The soil at the site is a well-drained, acid (pH 5.6) loamy Andisol with 1% slope. The concentration of nutrients in the top 25 cm of soil was me-

FIGURE 1. The field site at the Santa Catalina Experimental Station; in the background is Atacazo Mountain (3,700 m).

	H	G	F	E	D	C	B	A
H	HH	HG	HF	HE	HD	HC	HB	HA
G	GH	GG	GF	GE	GD	GC	GB	GA
F	FH	FG	FF	FE	FD	FC	FB	FA
E	EH	EG	EF	EE	ED	EC	EB	EA
D	DH	DG	DF	DE	DD	DC	DB	DA
C	CH	CG	CF	CE	CD	CC	CB	CA
B	BH	BG	BF	BE	BD	BC	BB	BA
A	AH	AG	AF	AE	AD	AC	AB	AA

A = Fertilized quinoa
B = Non-fertilized quinoa
C = Fertilized lupine
D = Non-fertilized lupine
E = Fertilized melloco
F = Non-fertilized melloco
G = Non-fertilized potato
H = Fertilized potato

FIGURE 2. Field layout for one replication. Letters in rows correspond to plots planted in 1993 and 1995; letters in columns correspond to plots planted in 1994. Diagonal plots correspond to monocrops.

dium in N and P, and high in K. The mean annual temperature is 12°C, and mean annual rainfall is 1,200 mm. The first planting was undertaken in 1993, and the experiment will be continued until 1998. The results of the first three years (1993–1995) are reported.

Four native Andean crops—lupine cv. Ecu3050; melloco cv. Ecu791; potato cv. Esperanza; and quinoa cv. Tunkahuan—were planted at two levels of fertilization. For each crop, zero fertilization was compared with the recommended rate (kg/ha N–P–K) as follows: melloco: 50–80–40; lupine: 20–60–40; potato: 200–300–100; and quinoa: 80–40–40. Quinoa and lupine were planted in rows 0.6 m apart, while potato and melloco were planted in rows 1.2 m apart, all on 23 m^2 plots. Neither herbicides nor pesticides were applied, except for potato where pre-plant Carbofuran (2,2–Dimethyl–2, 3–Dihydro Benzofuranyl–7–Methyl Carbamate) was used to prevent tuber damage by *Premnotripex vorax,* and three applications of Mancozeb (Mn-ethylene bisdithiocarbamate) were necessary to control foliar diseases.

TREATMENT ARRANGEMENT AND EXPERIMENTAL DESIGN

The fertilized and non-fertilized recurrent sequence of paired crops (rotations) and monocrops were assigned as treatments. Each of the three replications consisted of 64 plots (56 paired combinations plus 8 monocrops) arranged in a cross-pattern layout as shown in Figure 2. This arrangement was adapted from Hijink M. J. (no date) and allows the evaluation of the reciprocal combinations of paired crops in the same year (rotations), and at the same time comparison between combinations and monocrops. The treatments were assigned at random before the first planting date in 1993.

The response variables for the first year (1993) were analyzed using a Randomized Complete Block Design with eight treatments (the combination of four crops with two levels of fertilization) and three replications.

The results after the second year were analyzed using the following statistical linear model:

$$Y = \mu + Ri + CC_j + RxCC_{ij} + CF_k + CCxCF_{jk} + RxCCxCF_{ijk} + PC_l + RxPC_{il} + PF_m + PCxPF_{lm} + RxPCxPF_{ilm} + CCxPC_{jl} + RxCCxPC_{ijl} + CCxPF_{jm} + RxCCxPF_{ijm} + CFxPC_{kl} + CFxPF_{km} + CCxCFxPC_{jkl} + CCxPCxPF_{jlm} + CFxPCxPF_{klm} + CCxCFxPF_{jkm} + CCxPCxCFxPF_{jklm} + E_{ijklm}$$

Where: Y = response variable
μ = overall mean
R_i = i^{th} replication
CC_j = j^{th} current season's crop
CF_k = k^{th} current season's fertilizer
PC_l = l^{th} previous season's crop
PF_m = m^{th} previous season's fertilizer
and E_{ijklm} = experimental error.

The replication effect and its interactions were considered to be random. The statistical analysis was undertaken with SAS Institute's GLM procedure (SAS, 1992).

Crop yield (grain or tubers) and above-ground biomass were sampled in a 9.6 m^2 net plot for quinoa and lupine, and a 14.4 m^2 net plot for potato and melloco. The sampled data were transformed to Mg ha^{-1} and grain yield was adjusted to 14% moisture. In order to make comparisons between crops, grain yield (quinoa and lupine) and tuber yield (potato and melloco) were transformed to their energetic equivalent. These energy yields were calculated by multiplying the crop yield by its individual energetic coefficient (kcal/100g): quinoa = 353, melloco = 51, lupine = 346, and potato = 71 (INN, 1965). In 1995, it was not possible to evaluate biomass because a hailstorm caused defoliation in all crops when they were near physiological maturity.

RESULTS AND DISCUSSION

Since the experiment was initiated in 1993, the only possible effects for the analysis in this year were current season crop (CC), current season fertilizer (CF), and their interaction. The CCxCF interaction was significant for crop yield, energy equivalent yield, and biomass per plant. The number of weeds m^{-2} was influenced only by the CC main effect.

Fertilizer increased the marketable yield of potato (52%), melloco (18.5%), and quinoa (23%) in 1993 (Table 1). Along with this increment in yield, an increase in energy equivalent yield and biomass was observed when fertilizer was used. In contrast, the response of lupine to fertilizer was negative. Marketable and energy equivalent yield of fertilized lupine decreased by 41 and

TABLE 1

Current crop × current fertilizer interaction for crop yield, energy equivalent yield, biomass and weed population in 1993

CC × CF	Crop yield (Mg ha^{-1})	Energy yield (Mcal ha^{-1})	Biomass[†] (g $plant^{-1}$)	Weeds (Weed m^{-2})
Potato × F[‡]	20.84	14800.91	262.97	344[§]
Potato × NF	9.91	7033.18	117.27	
Melloco × F	8.43	4298.69	165.75	210
Melloco × NF	6.87	3504.04	97.05	
Lupine × F	0.32	1127.3	382.82	104
Lupine × NF	0.51	1767.14	377.64	
Quinoa × F	1.59	5623.84	23.31	282
Quinoa × NF	1.22	4323.63	17.03	

[†] Total biomass includes above ground dry matter plus marketable yield (tubers in potato and melloco, and grain in quinoa and lupine).

[‡] F is fertilized and NF is not fertilized.

[§] Current crop main effect is reported in this column.

TABLE 2
Summary of statistical analyses for the fixed effects in the model for 1994 and 1995

	Crop yield		Energy yield		Biomass		Weeds	
Source	1994	1995	1994	1995	1994	1995	1994	1995
CC[§]	0.002[†]	0.001	0.005	0.001	0.008	ns[‡]	ns	0.001
CF	0.001	0.017	0.001	0.041	0.005	ns	0.084	0.018
PC	ns	ns	ns	ns	ns	0.034	ns	ns
PF	ns	ns	ns	ns	ns	ns	ns	0.001
CC × CF	0.001	0.057	0.001	0.100	0.016	ns	0.076	0.009
PC × CC	ns	0.014	ns	0.001	ns	ns	0.021	ns
PF × CC	ns	ns	ns	ns	0.023	ns	ns	0.045
PF × CF	ns	ns	ns	ns	0.133	ns	0.125	ns
PC × PF	ns	ns	ns	ns	ns	ns	ns	0.041
PC × CC × CF	ns	0.003	ns	0.001	ns	0.038	ns	ns
PC × PF × CF	ns	ns	0.150	ns	ns	ns	ns	ns
PC × PF × CC	0.144	ns	0.074	ns	ns	ns	ns	ns

[†] Value indicates p > F.

[‡] ns = non-significant effect.

[§] CC = Current season Crop, CF = Current season Fertilizer, PC = Previous season Crop, PF = Previous season Fertilizer.

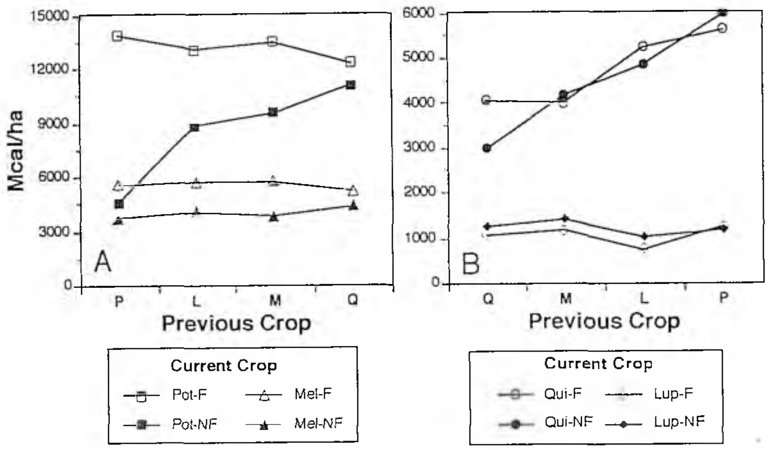

FIGURE 3. Previous crop × current crop × current fertilizer interaction for energy equivalent yield of (A) tubers and (B) grains in 1995.
(Standard Error = 628 Mcal/ha^{-1})

43% respectively, while a slight (2%) increase in biomass was observed. Lupine reduced weed populations more than any other crop. Even though the tuber crops required four cultivations during the season, the weed population was 74% higher in potato and 51% higher in melloco than in lupine, where only two cultivations were needed (Table 1).

A summary of the results of the statistical analyses for 1994 and 1995 is shown in Table 2. Similar to the 1993 findings, CC, CF, and the interaction CCxCF were significant, and they explained most of the variability in the response variables analyzed. In addition, the effects of PC and PF were detected in several interactions in both 1994 and 1995. One of the most noteworthy interactions in 1995 was PCxCCxCF (Figure 3). The tuber species increased their energy equivalent yields when fertilizer was applied, except when quinoa was the PC (Figure 3A). Fertilized quinoa had a higher energy equivalent yield than non-fertilized quinoa only in monocropping, while lupine responded negatively to fertilization (Figure 3B). This effect was also observed in 1993, and will be discussed in detail in the following paragraphs. Energy equivalent yields of non-fertilized potato after melloco, lupine, and quinoa where at least 50% higher than in monocropping (Figure 3A). Unlike potato, where the response to previous crop occurred only in non-fertilized plots, both fertilized and non-fertilized quinoa responded positively to PC (Figure 3B). Melloco and lupine did not respond to the previous crop.

Tables 3 and 5 summarize the PF effect on the current

TABLE 3

Previous season fertilizer (PF) effect on yield, energy equivalent yield, biomass, and weed population of the current season crop (CC) in 1994

PF	CC	Crop yield (Mg ha^{-1})	Energy yield (Mcal ha^{-1})	Biomass† (g $plant^{-1}$)	Weeds (Weeds m^{-2})
F	Potato	8.56	6078.76	210.88	486.50
NF	Potato	7.99	5670.67	216.54	454.66
F	Melloco	3.40	1735.34	64.10	325.33
NF	Melloco	3.42	1745.21	79.10	316.33
F	Lupine	0.30	1036.41	185.25	417.36
NF	Lupine	0.38	1325.52	147.82	410.00
F	Quinoa	1.00	3514.59	111.45	431.50
NF	Quinoa	0.80	2819.36	97.17	460.83

†Total biomass includes above ground dry matter plus marketable yield (tubers in potato and melloco, and grain in quinoa and lupine).

TABLE 4

Previous season crop (PC) effect on yield, energy equivalent yield, biomass, and weed population of the current season crop (CC) in 1994

PC	CC	Crop yield (Mg ha^{-1})	Energy yield (Mcal ha^{-1})	Biomass† (g $plant^{-1}$)	Weeds (Weeds m^{-2})
Potato	Potato	8.24	5849.57	196.68	535
Melloco	Potato	8.20	5820.82	220.93	423
Lupine	Potato	8.54	6060.43	221.06	450
Quinoa	Potato	8.12	5767.59	91.96	473
Potato	Melloco	4.23	4225.00	70.35	287
Melloco	Melloco	2.74	2753.83	55.57	318
Lupine	Melloco	3.43	3427.50	89.86	324
Quinoa	Melloco	3.26	3262.50	70.75	352
Potato	Lupine	0.37	1274.76	201.36	393
Melloco	Lupine	0.31	1048.71	164.62	464
Lupine	Lupine	0.32	1111.92	135.23	408
Quinoa	Lupine	0.37	1288.47	164.89	390
Potato	Quinoa	0.95	3367.03	128.85	486
Melloco	Quinoa	1.10	3778.10	79.60	474
Lupine	Quinoa	0.99	3522.69	116.84	426
Quinoa	Quinoa	0.57	2000.07	91.96	398

†Total biomass includes above ground dry matter plus marketable yield (tubers in potato and melloco, and grain in quinoa and lupine).

season crop for 1994 and 1995, respectively. Current crop (CC) conceals the effect of the current season fertilizer. Marketable potato yields were 0.57 Mg ha^{-1} (7%) higher in 1994 and 1.07 Mg ha^{-1} (7%) higher in 1995 on plots fertilized the previous season than potato planted in plots not fertilized the previous season. Quinoa yields were 0.2 Mg ha^{-1} (20%) higher in 1994 and 0.1 Mg ha^{-1} (–8%) lower in 1995 when planted in plots fertilized the previous season. Melloco did not respond to previous season fertilization, and lupine responded negatively to the previous season fertilization. Lupine yields were 27% lower in 1994 and 24% lower in 1995 when planted in plo fertilized the previous season. Similar trends were o served for energy equivalent yields in all four crops.

The best method to evaluate crop rotation is by th effect of the previous crop. In our experiment the P effect was present in interaction with other factors f several variables. Tables 4 and 6 summarize the previo season crop effect on the current season crop for 199 and 1995, respectively. Again, CC conceals the effect the current season fertilizer. Monocropping reduced ma ketable and energy equivalent yields of quinoa and me

TABLE 5

Previous season fertilizer (PF) effect on yield, energy equivalent yield, biomass, and weed population of the current season crop (CC) in 1995

PF	CC	Crop yield (Mg ha^{-1})	Energy yield (Mcal ha^{-1})	Weeds (Weeds m^{-2})
F	Potato	15.71	11,157.8	822.3
NF	Potato	14.64	10,394.2	984.7
F	Melloco	9.36	4772.9	708.0
NF	Melloco	9.04	4609.6	770.6
F	Lupine	0.29	999.1	285.1
NF	Lupine	0.36	1238.4	349.3
F	Quinoa	1.25	4421.6	429.0
NF	Quinoa	1.35	4764.3	370.0

TABLE 6

Previous season crop (PC) effect on yield, energy equivalent yield and weed population of the current season crop (CC) in 1995

PC	CC	Crop yield (Mg ha^{-1})	Energy yield (Mcal ha^{-1})	Weeds (Weeds m^{-2})
Potato	Potato	12.94	9188.5	906
Melloco	Potato	16.11	11,436.4	830
Lupine	Potato	15.31	10,872.3	924
Quinoa	Potato	16.35	11,606.9	954
Potato	Melloco	8.95	4567.0	746
Melloco	Melloco	9.22	4703.6	731
Lupine	Melloco	9.42	4802.9	716
Quinoa	Melloco	9.20	4691.4	763
Potato	Lupine	0.35	1197.4	300
Melloco	Lupine	0.37	1281.5	319
Lupine	Lupine	0.24	856.9	326
Quinoa	Lupine	0.33	1139.3	329
Potato	Quinoa	1.64	5783.3	366
Melloco	Quinoa	1.15	4067.3	399
Lupine	Quinoa	1.42	5007.9	375
Quinoa	Quinoa	1.00	3513.7	457

loco in 1994, and of quinoa, potato, and lupine in 1995 (Tables 4 and 6). As with the PF effect, melloco and lupine did not respond to the PC effect in 1994 or in 1995. In contrast, the influence of PC on quinoa was remarkable. Marketable yields of quinoa in rotation were 66–92% (1994), and 15–64% (1995) higher than in monocropping. Potato followed the same trend in 1995, where rotation increased tuber yields 18–23%. In general, potato following quinoa, and quinoa following potato appeared to be the most productive paired rotations. These results confirm previous research reported in the region. For instance, the rotations: quinoa–potato–lupine–quinoa, and quinoa–potato–potato–quinoa, are recommended for the mountainous areas of Peru (Lescano and Zeballos, 1982). The rotation, potato (fertilized)–quinoa (not fertilized), was validated as an alternative for Ecuador's highlands, because the fertilizer residuals left by potato are used by quinoa (INIAP, 1992). In temperate regions, potato yields without N fertilizer were up to 15 t ha^{-1} higher when planted after legumes (alfalfa and red clover), and this beneficial effect carried over to the second and third year. Also, the optimum rate of N fertilizer needed when potato was planted after legumes was 67 to 99 kg ha^{-1} less than that after oats (Neeteson, 1989).

In subsistence agricultural systems like those commonly found in the Andean region, a major concern is how to decrease the use of external inputs without reducing yields. After the first three years of this research at the Santa Catalina Experimental Station, the response of the paired crop rotations without fertilizer was summarized (Table 7). Although quinoa–potato, melloco–potato, and potato–quinoa appeared to be good rotations in 1995 (data not shown), the most consistent option for non-fertilized systems is the use of lupine as previous crop. Marketable yields of non-fertilized quinoa and potato planted after non-fertilized lupine were from 44 to 188% higher than their non-fertilized monocrops in 1994 and 1995. Non-fertilized melloco planted after non-fertilized lupine had 28% higher yields than its non-fertilized monocrop in 1994 (Table 7).

Even when the effect of fertilization is concealed by the interaction PCxCC, lupine as previous crop exerted a consistently positive influence on marketable and energy yields of quinoa, potato, and melloco in 1994 and 1995 (Tables 4 and 6). Increased crop yields following lupine could be the result of organochemical by-products left in the soil after lupine harvest. It has been suggested that growth-promoting substances in legume residues are responsible for some beneficial effects for the following crop in the rotation. For instance, triacontanol, an alcohol extracted from legumes, was reported as a stimulant of plant growth for other crops (Crookston *et al.*, 1988). Proteoid roots synthesize higher amounts of citrate and malate for exudation, compared to normal roots. Citrate exudates into the rhizosphere increase the P available to the plant by mobilizing the soluble mineral P and possibly organic P sources. *Lupinus albus* is able to enhance the proteoid root formation in the presence of P deficiency in amounts as high as 23% of its total plant dry weight (Johnson *et al.*, 1996). *Lupinus mutabilis* is also able to free blocked soil phosphorus (Gross, 1982). Increased availability of nutrients such as Fe, Cu, and Zn due to the microbial-chelation process may also be an effect of crop rotation with legumes (Karlen *et al.*, 1994).

TABLE 7
Effect of non-fertilized lupine or monocropping as PC on marketable yield of non-fertilized current crop in 1994 and 1995

		Marketable yield ($Mg\ ha^{-1}$)	
PC	CC	1994	1995
Lupine	Potato	4.75 (+48)[†]	9.76 (+44)
Potato	Potato	3.20	6.78
Lupine	Quinoa	0.93 (+98)	1.38 (+188)
Quinoa	Quinoa	0.47	0.48
Lupine	Melloco	3.42 (+28)	6.36 (–4)
Melloco	Melloco	2.68	6.64

[†] Numbers in parenthesis represent % yield increment over the monocrops.

The effects of PF and PC on weed populations in 1994 and 1995 were not clear. However, lupine as CC, and certain paired crop arrangements (melloco–potato, quinoa–potato, and quinoa–lupine) substantially decreased weed populations (Tables 4 and 6). Plots planted with lupine in 1995 had 586 weeds m^{-2} less than potato, 422 weeds m^{-2} less than melloco, and 83 weeds m^{-2} less than quinoa. These results are consistent with what was observed in 1993. Shade provided by the canopy of grain species (lupine and quinoa) appears to be the main source of weed population depletion. These results are in agreement with Gross (1982), who indicated that lupine is specially planted in crop rotations to control weeds by shading.

An increase in total number of weeds was observed as an effect of crop rotation from 1993 to 1995 (Tables 1, 4, and 6). It has been suggested that crop rotations can be a source of weed problems. Long-term rotations with cereals and sod crops resulted in an increase of perennial weed populations, and this is seen as a negative effect of crop rotation (Sieczka, 1989). In this experiment, the weed population increase during the three seasons can be explained as a consequence of the suppression of herbicide application after 1992. In locations where weed

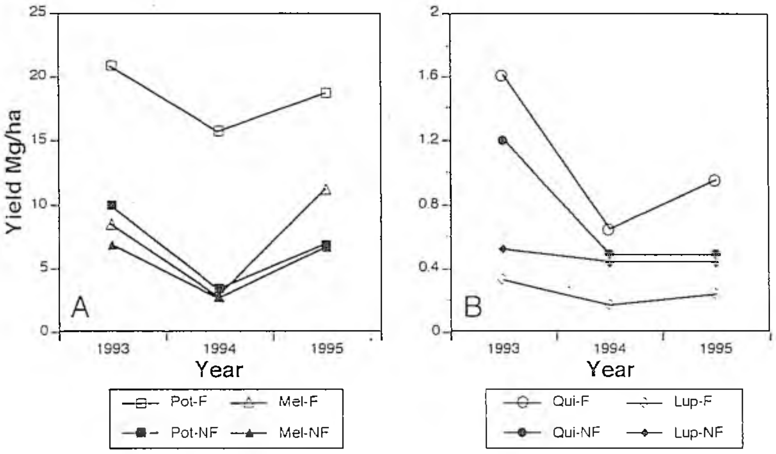

FIGURE 4. Fertilizer effect on marketable yield of four Andean crops during three years of monocropping.

species diversity and density are high, such as the fields at the Santa Catalina Experimental Station, the use of crop rotation is not sufficient to control weeds. As Forcella and Lindstrom (1988) suggested, a complementary use of herbicides and rotation is needed to achieve adequate weed control.

After the first three years of the experiment. it was also possible to evaluate the effects of monocropping, regardless of fertilization level. The decline in marketable yield was significant for potato and quinoa, negligible for lupine, and unpredictable for melloco (Figure 4). In monocropping, the negative response of lupine to fertilization was exposed clearly during the three years of the experiment. Yields of fertilized lupine were up to 37% lower than non-fertilized lupine (Figure 4B). Yield reduction observed in monocropped potato may be due to the increase in pest populations. Monocropped potato had higher levels of *Verticillum dahliae* in both infested and non-infested soils, compared to potato in rotation with barley and bean (Mol *et al.*, 1995). Increasing the frequency of potato monocropping together with application of nematicides resulted in increased infection of stems and stolons by *R. solani,* compared to crop rotations (Scholte, 1987; Honeycutt *et al.*, 1996). Figure 4 also shows unusually low yields for all the crops in 1994, probably due to an excess of precipitation (355 mm above annual average) that reduced growth and yield.

CONCLUSIONS

Based on the results obtained after the first three years of the experiment, it is possible to envision some of the long-term implications of the study. Yields of monocropped potato and quinoa were reduced regardless of fertilization regime. This trend is expected to continue for both crops, especially in the non-fertilized plots. Weed populations were not affected by previous crop or previous fertilizer, but a substantial decrease was observed when lupine and quinoa were the current season crops. It is noteworthy that these crops require two or three less cultivations than the tuber crops, and still they reduce weed populations. One possible explanation for this is the shade projected by the crops' canopies.

Lupine(NF)–quinoa, lupine(NF)–melloco, potato(F)–quinoa(NF), melloco–quinoa, and lupine(NF)–potato appear to be the best paired combinations for yield and biomass production under these climatic and soil conditions in Ecuador

ACKNOWLEDGEMENTS

This paper is a contribution of the Santa Catalina Experimental Station (INIAP-Ecuador) and Department of Agronomy, University of Nebraska-Lincoln. Funds supporting field research were provided by the International Development and Research Center (IDRC) of Canada (Project 3P-90-160 INIAP-IDRC).

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