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PATRON DE EXTRACCION Y REQUERIMIENTOS DE AGUA EN DIFERENTES ETAPAS FENOLOGICAS EN EL NOGAL

Depletion Pattern and Water Requirements in Different Phenological Stages of Pecans

Claudio Godoy Avila[1] y J. Cristián López Ch.

RESUMEN

La disponibilidad de información relacionada con los requerimientos de agua por el nogal pecanero (*Carya illinoensis* K.), en diferentes edades y a través de diferentes etapas fenológicas, es escasa. En busca de este conocimiento, durante cuatro años (1991, 1992, 1993 y 1994) se realizó un estudio con el propósito de determinar los requerimientos de agua para este cultivo, las posiciones de mayor o menor extracción de agua dentro de la zona de goteo del árbol y a través de sus diferentes etapas fenológicas. Se seleccionaron cuatro árboles con un diámetro de tronco similar y se colocaron 36 tubos de aluminio para el acceso de la sonda de neutrones, en forma equidistante alrededor del árbol y a una distancia de un metro entre ellos. Se encontró que el uso de agua (cm d^{-1}) en los diferentes períodos considerados, así como el consumo total por ciclo, se incrementó en función de la edad de los árboles. El abatimiento de la humedad y consumo total de agua fue similar en todos los puntos de muestreo dentro de la copa del árbol, denotando que la actividad de raíces fue similar en todas las posiciones. La fase de llenado de la almendra resultó ser la etapa de mayor demanda de agua.

Palabras clave: *Requerimientos de agua, etapa fenológica, uso de agua, patrón de extracción de agua.*

SUMMARY

Information related to water requirements through different ages and phenological stages in pecans (*Carya illinoensis* K.) is scarce. During 1991, 1992, 1993 y 1994, a study was conducted to determine the water requirements in this crop and to know the water depletion pattern inside the tree drip zone and through the different phenological phases. Four trees of similar trunk diameter were selected, placing around each tree in an equidistant arrangement 36 aluminum tubes for the access of the neutron probe. It was found that, in the different phenological stages, the water use (cm d^{-1}) and total water consumption per cycle, were increased with the age of trees. The total water consumption was very similar in all positions inside of the drip zone, denoting a similar root activity in all positions. The nut filling was the phase of higher water consumption.

Index words: *Water requirements, phenological phase, water use, water depletion pattern.*

INTRODUCCION

En México, las zonas productoras de nuez pecanera se ubican en el norte, principalmente en los estados de Chihuahua, Coahuila, Nuevo León, Sonora y Durango. La superficie ocupada por este cultivo es de 50 mil hectáreas, las cuales para su producción comercial deben de ser irrigadas, usándose en un alto porcentaje de esta superficie el agua del subsuelo (Godoy, 1994). La lámina de agua que se aplica a este cultivo es de 1.6 a 2.0 m por año, en un número de riegos que va de ocho a diez. Se estima que del total de los costos del cultivo, 50 % corresponde al uso y manejo del agua (Godoy, 1977; Hernández, 1990).

La información relacionada con los requerimientos de agua por este cultivo es todavía escasa. Además, el consumo de agua registrado durante la estación de crecimiento varía entre regiones, cultivares, edad y número de árboles por hectárea y etapa fenológica del cultivo. Por ejemplo, en El Paso, Texas, el consumo de agua en árboles maduros es 18 cm por mes durante el verano (Romberg, 1960) y de 100 a 130 cm por ciclo (Miyamoto, 1983; Thompson, 1974); en el área de Las Cruces, Nuevo México, varía de 68 a 100 cm por ciclo (Warrick *et al.*, 1980); en Ramos Arizpe, Coahuila, el consumo máximo reportado fue de 96.1 cm (Hernández, 1984; Jasso, 1988) y en la Comarca

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Lagunera fue de 115 cm, en un estudio que duró cuatro años consecutivos (Faz *et al.*, 1980; Godoy, 1977). Por consiguiente, es necesario conocer los requerimientos de agua y las características del uso del agua en el nogal (patrón de extracción de agua, zona de mayor extracción, etc.) para hacer una mejor planeación y calendarización de los riegos en este cultivo, y así incrementar la eficiencia en su uso. En relación con lo anterior, durante 1991, 1992, 1993 y 1994, se realizó un estudio cuyos objetivos fueron los siguientes:

- Determinar los requerimientos de agua para este cultivo a través de diferentes períodos de su desarrollo y a través de los años.
- Determinar las zonas de mayor o menor extracción de agua dentro de la zona de goteo del árbol y a través de las diferentes etapas fenológicas.

MATERIALES Y METODOS

El presente estudio se realizó en el área de influencia del CIFAP-Comarca Lagunera (Centro de Investigaciones Forestales, Agrícolas y Pecuarias de la Comarca Lagunera), ubicado en Matamoros, Coahuila, México. Antes de iniciar el estudio se tomaron muestras de suelo para determinar la textura y los parámetros de capacidad de campo (cc) y punto de marchitez permanente (pmp). Estos datos se muestran en el Cuadro 1. Se utilizó una huerta comercial bien manejada, la cual fue plantada con el cultivar Western. Cuando se inició el estudio, los árboles contaban con doce años de edad, estaban sanos y su tamaño era uniforme. Se irrigó la huerta usando el método superficial con agua proveniente del subsuelo (0.288 dS m^{-1}; pH de 8.07 y 0.74 meq L^{-1} de Na). Se aplicaron los riegos cuando el almacenamiento del agua del suelo a una profundidad de 90 cm alcanzaba 50 % de la humedad disponible (Godoy, 1977; Miyamoto, 1983). Antes de iniciar el estudio, se escogieron cuatro árboles con un diámetro de tronco similar y competencia completa dentro de la huerta. Se colocaron 36 tubos de aluminio en forma equidistante alrededor de cada árbol, a una distancia de un metro entre ellos, tal como lo muestra la Figura 1. Se tomaron lecturas con la sonda de neutrones cada semana, desde la brotación hasta la maduración del fruto, a tres profundidades que fueron 0 a 30, 30 a 60 y 60 a 90 centímetros. El consumo de agua a mayor profundidad no se midió, debido a que se ha encontrado que el sistema radical del nogal rara vez excede los 90 centímetros (Godoy, 1994; Miyamoto, 1983). Es importante señalar que, en el estudio, la superficie del suelo se cubrió con plástico negro con el propósito de evitar la evaporación directa del suelo (Eo) y así cuantificar únicamente el agua usada a través de la transpiración del árbol.

Para la calibración de la sonda de neutrones, se tomaron lecturas en los 36 tubos de acceso a tres profundidades en intervalos de 30 cm; posteriormente se procedió a tomar muestras de suelo para la determinación de humedad base peso seco. Mediante un análisis de regresión, se obtuvieron los parámetros de los modelos de regresión para los tres estratos de suelo, el cual resultó ser lineal, debido a que éste presentó los coeficientes de correlación más altos cuando fue comparado con otros modelos de ajuste. A continuación se muestran los parámetros de dicho modelo:

Estrato	Modelo de regresión	r^2
cm		
00 a 30	Y = - 0.55 + 7.66 X	0.94
30 a 60	Y = 1.92 + 6.71 X	0.94
60 a 90	Y = -10.50 + 11.74 X	0.91

donde:
Y = Humedad base peso seco (%)
X = Radio de conteo

Se calculó el consumo de agua usando la siguiente ecuación:

$$CA = (A_1 - A_2)(D_a)(P_r)$$

donde:
CA = Consumo de agua (cm)
A_1 = Humedad anterior (%)
A_2 = Humedad actual (%)
D_a = Densidad aparente del suelo (g cm^{-3})
P_r = Profundidad radical (cm).

RESULTADOS Y DISCUSION

En el Cuadro 2 se muestra el uso de agua por el nogal (cm d^{-1}) en diferentes períodos, así como el consumo total para los cuatro años de estudio. Se observa que para el año en que se inició el experimento, en el período comprendido desde antes de la brotación hasta el inicio de la brotación (22 de enero a 26 de marzo), el consumo de agua fue bajo, siendo su valor 0.11 cm d^{-1}; mientras que desde la brotación

Cuadro 1. Textura y constantes de la humedad del suelo del sitio experimental.

Profundidad	Clasificación textural	Capacidad de campo	Punto de marchitez permanente
cm		%	%
00 a 30	Migajón-arcillo-arenoso	27.2	14.0
30 a 60	Migajón-arenoso	24.5	12.9
60 a 90	Migajón-arcillo-arenoso	28.4	15.2

Cuadro 2. Consumo de agua promedio (cm d^{-1}) en diferentes fases fenológicas del nogal pecanero cv. Western en un período de cuatro años.

Año	Diámetro tronco	Antes de brotación a brotación	Brotación a receptividad del estigma	Receptividad del estigma a llenado de la almendra	Llenado de la almendra	Total
	cm					
1991	17	0.11	0.16	0.20	0.25	46.8
1992	22	0.12	0.19	0.25	0.30	56.4
1993	25	0.13	0.25	0.32	0.40	72.8
1994	30	0.15	0.30	0.37	0.43	81.4

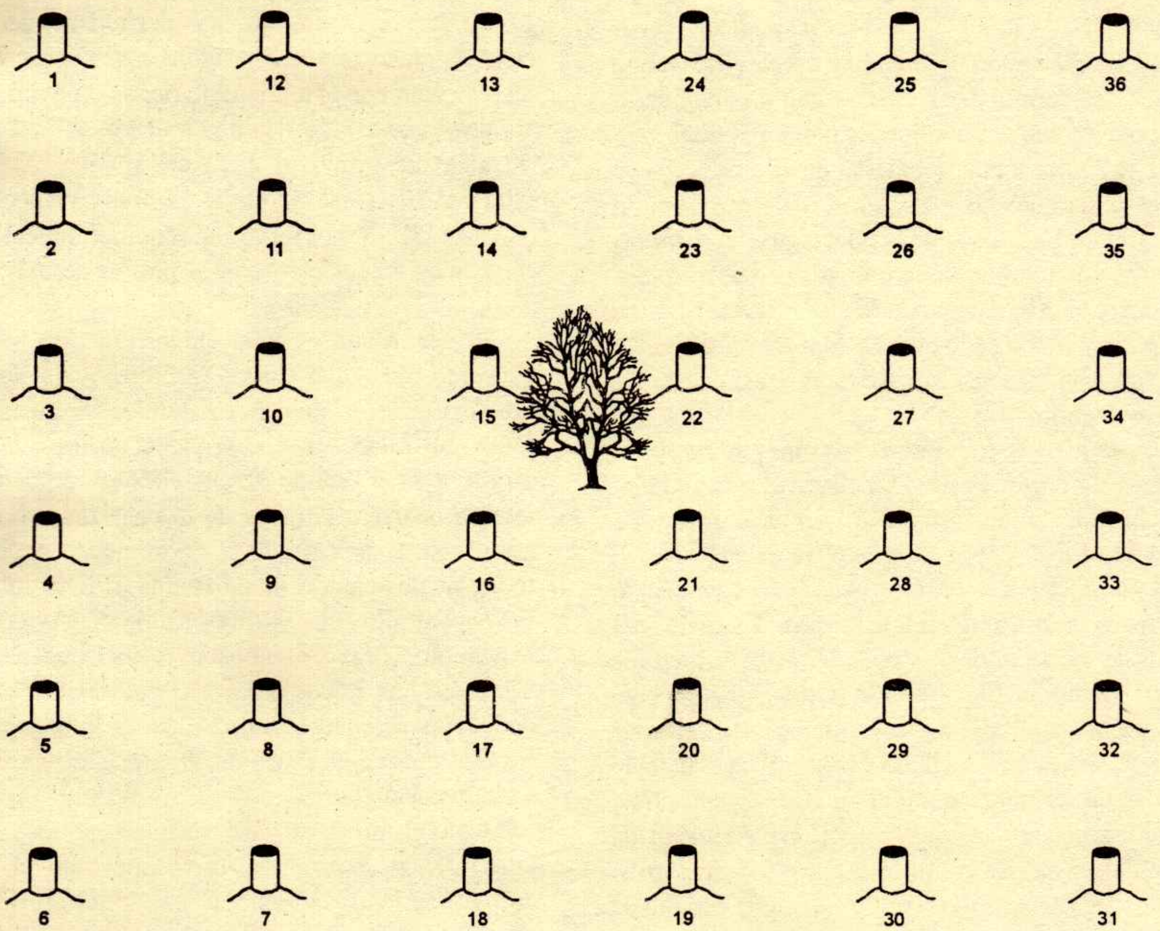

Figura 1. Ubicación de los tubos de aluminio para muestreo de humedad en el nogal cv. Western.

hasta el inicio en el llenado del fruto (26 de marzo a 23 de julio) se incrementó de manera significativa, alcanzando valores de 0.16 a 0.20 cm día^{-1}. Durante el llenado de la almendra (23 de julio a 17 de septiembre) los valores de consumo de agua fueron más altos que en los otros períodos, del orden de 0.25 cm día^{-1}. Este incremento en el consumo de agua durante el llenado del fruto provee condiciones favorables para el buen funcionamiento del árbol (absorción y transporte de nutrimentos, fotosíntesis y translocación de fotosintatos) (Godoy, 1994).

El uso de agua en los diferentes períodos considerados, así como el consumo total, se incrementaron a través de los años, esto indica que a medida que los árboles aumentan su tamaño, tanto en su diámetro de copa o diámetro del tronco, sus requerimientos de agua también se incrementan de una manera significativa (Cuadro 2). Estos resultados son similares a los reportados por Miyamoto (1983) y Privette (1979), quienes encontraron valores de consumo de 0.27 cm d^{-1} de la brotación a la receptividad del estigma y de 0.42 cm d^{-1} durante el llenado del fruto. Estos consumos se estimaron para una huerta cuyos árboles tenían características similares (diámetro de tronco de 25 cm y una población de 70 árboles ha^{-1}) a las que tenían los árboles en el presente estudio durante 1993. Los consumos de agua reportados (Cuadro 2) fueron un poco más bajos que los encontrados por Miyamoto (1983) y Privette (1979), debido, principalmente, a que la superficie del suelo fue cubierta con plástico, reduciéndose así la Eo de una manera significativa.

En el Cuadro 3 se presenta el consumo de agua por estrato de suelo durante 1993. Se observa, por un lado, que el consumo total promedio por árbol fue de 72.8 cm (Cuadro 2) y, por otro lado, se observa que el consumo de agua en el estrato 30 a 60 cm, y debido probablemente a un cambio en la textura del suelo, fue inferior al de los estratos 0 a 30 y 60 a 90 cm, en los cuales el consumo fue similar, siendo ligeramente superior en el estrato 0 a 30 centímetros. El menor consumo de agua en el segundo estrato probablemente se debió a un cambio en la textura del suelo. Este patrón de extracción de agua denota una actividad de raíces similar hasta una profundidad de 90 centímetros. Sin embargo, es necesario recordar que en el estudio se cubrió el suelo con plástico con el propósito de eliminar la Eo, la cual durante la primavera es muy

Cuadro 3. Agua extraída por arboles de nogal cv Western a tres profundidades de suelo durante el año de 1993.

Profundidad (cm)	Extracción de agua (cm)	(%)
00-30	27.90	38.30
30-60	20.89	28.70
60-90	24.01	37.00
Total	72.80	100.00

significativa y esto posiblemente hace que la extracción de agua en los tres estratos sea similar, ya que si no se eliminan las pérdidas por Eo, el patrón de extracción de humedad cambia, incrementándose en el estrato 0 a 30 centímetros. En algunos estudios realizados en este cultivo (Avalos, 1994; Miyamoto, 1983), se ha encontrado que el consumo de agua por estratos ocurre de acuerdo con la forma de un prisma, con un consumo más grande hacia la superficie del suelo, producto de una mayor pérdida de agua por Eo en el estrato 0 a 30 centímetros. Miyamoto (1983) estimó valores de 14 a 17 cm de evaporación de la superficie del suelo, en un ciclo de cinco riegos, y establece que estos valores se incrementan con el número de riegos o lluvia. En suma, alrededor de 38 % del agua usada por el nogal es extraída del estrato 0 a 30 cm y 29 y 33 % de los estratos 30 a 60 y 60 a 90 cm, respectivamente (Cuadro 3). Se observó un comportamiento similar entre años en relación con el patrón de extracción de humedad.

En la Cuadro 4 se muestran los valores de consumo de agua total (promedio de los cuatro árboles) en cada uno de los puntos de muestreo para 1993. Se puede observar que contrario a lo que se especula en el sentido de que el consumo de agua más intenso ocurre a la orilla de la copa del árbol, en este estudio se encontró que el consumo de agua total en todas las posiciones fue muy similar. Esto coincide con lo encontrado en varios estudios (Avalos, 1994; Miyamoto, 1983; Thompson, 1974) que han demostrado que las raíces del nogal con edades de más de doce años de edad se entrecruzan, y esto parcialmente explica porque el consumo de agua fue independiente de la distancia horizontal.

Con el propósito de verificar si los resultados anteriores se repetían a través de todo el ciclo del cultivo, en los Cuadros 5 y 6 se muestran los valores de humedad en el estrato 0 a 30 cm, ocho días después de que se aplicó el riego, en dos fechas diferentes, que

Cuadro 4. Consumo de agua por posición dentro de la zona de extracción en nogal. 1993 (ver Figura 1).

Posición	Consumo de agua	Posición	Consumo de agua	Posición	Consumo de agua
	cm d^{-1}		cm d^{-1}		cm d^{-1}
1	73.4	13	72.9	25	73.9
2	70.3	14	74.1	26	72.9
3	73.3	15	73.9	27	74.3
4	72.2	16	72.3	28	73.0
5	74.2	17	73.0	29	72.9
6	71.6	18	73.8	30	73.6
7	71.9	19	72.0	31	73.3
8	72.2	20	70.8	32	70.3
9	73.4	21	73.4	33	73.3
10	70.4	22	74.8	34	73.2
11	72.0	23	72.0	35	73.8
12	73.6	24	72.9	36	73.2

Cuadro 5. Valores de humedad en cada punto de muestreo dentro de la zona de goteo de el nogal durante el crecimiento del fruto en 1993 (ver Figura 1).

Posición	Consumo de agua	Posición	Consumo de agua	Posición	Consumo de agua
	cm d^{-1}		cm d^{-1}		cm d^{-1}
1	17.37	13	17.54	25	16.93
2	16.93	14	16.30	26	17.39
3	17.93	15	17.58	27	17.17
4	16.75	16	17.06	28	18.44
5	16.63	17	15.81	29	17.63
6	17.53	18	17.33	30	17.84
7	17.37	19	18.69	31	17.95
8	16.89	20	16.98	32	18.00
9	16.24	21	17.98	33	18.03
10	16.71	22	17.93	34	16.43
11	16.57	23	17.76	35	17.58
12	17.05	24	16.51	36	17.00

fueron 17 de junio, que es cuando ocurrió el crecimiento del fruto y 19 de agosto, que es cuando está ocurriendo el llenado de la almendra, respectivamente. Se usaron estas fechas con el propósito de observar si a medida que los requerimientos de agua del nogal se iban incrementando (Cuadro 2), se presentaban cambios en los valores de porcentaje de humedad por posición dentro del árbol. Los resultados confirman que, en términos generales, los valores de humedad en las dos fechas estudiadas fueron similares en todas las posiciones, siendo menores los valores pero similares entre posiciones a medida que la nuez estaba completando su llenado. Estos bajos valores de humedad denotan un consumo de agua más alto durante esta etapa de llenado de almendra (Cuadro 1). Lo anterior significa que para estudios posteriores y donde se quiera conocer los requerimientos de agua del nogal, el número de posiciones (tubos de aluminio)

Cuadro 6. Valores de humedad en cada punto de muestreo dentro de la zona de goteo de el nogal durante el llenado del fruto en 1993 (ver Figura 1).

Posición	Consumo de agua	Posición	Consumo de agua	Posición	Consumo de agua
	cm d^{-1}		cm d^{-1}		cm d^{-1}
1	21.30	13	22.81	25	22.84
2	22.00	14	21.83	26	20.23
3	20.30	15	23.35	27	21.94
4	20.00	16	22.35	28	23.92
5	22.05	17	21.60	29	23.82
6	20.17	18	19.05	30	22.45
7	22.68	19	22.21	31	23.70
8	23.29	20	19.59	32	22.01
9	20.67	21	22.18	33	22.73
10	21.97	22	19.30	34	20.70
11	20.90	23	22.50	35	22.70
12	22.90	24	20.57	36	23.00

dentro del árbol se puede disminuir en forma considerable con el propósito de ahorrar tiempo sin perder precisión en la información.

CONCLUSIONES

- A medida que los árboles incrementan su tamaño, el uso de agua en los diferentes períodos considerados, así como el consumo total de agua, se incrementa de manera significativa. El llenado de la almendra es la etapa de mayor demanda de agua.
- El consumo de agua por el nogal es independiente de la distancia horizontal; es decir, el consumo de agua total es muy similar en todas las posiciones dentro de la copa del árbol. Esto se repite a través de los diferentes períodos fenológicos estudiados.
- En el presente estudio se encontró que la mayor actividad de raíces fue similar entre estratos, a excepción del estrato 30 a 60 cm en que ésta disminuyó debido a un cambio en la textura del suelo.

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EFECTO DE LA MICORRIZA VESICULO-ARBUSCULAR SOBRE EL CRECIMIENTO Y DISTRIBUCION DE BIOMASA DE PLANTULAS DE EUCALIPTO

Effect of Vesicular-Arbuscular Mycorrhiza on Growth and Biomass Allocation of *Eucaliptus* Seedlings

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RESUMEN

Con el objetivo de evaluar el efecto de la endomicorrización sobre el crecimiento inicial y distribución de biomasa de *E. camaldulensis* y *E. globulus*, se inocularon plántulas de estas especies con cuatro cepas endomicorrízicas (*Glomus* sp. Zac.-2, *Glomus* sp. Zac.-19, *Glomus intraradix* Extranjera y *Glomus aggregatum*) y se comparó su desarrollo con el de plántulas no inoculadas, durante un período de 15 semanas. Las cepas de *Glomus* sp. (Zac.-2 y Zac.-19) promovieron los mayores incrementos en el crecimiento en altura y producción de biomasa (37 % y 35 %, con respecto al testigo) en las dos especies de eucalipto, a pesar de que fueron las cepas que presentaron el menor porcentaje de colonización (29 %). Por el contrario, *G. aggregatum* presentó los mayores porcentajes de colonización endomicorrízica (54 %), aunque fue la cepa endomicorrízica que afectó menos el crecimiento de las plántulas. La relación parte aérea/raíz aumentó en 17 % en las plántulas micorrizadas con las cepas Zac.-2 y Zac.-19, debido probablemente a una mayor eficiencia del sistema radical en la absorción de agua y nutrimentos. Las plántulas de *E. camaldulensis* mostraron una mejor respuesta a la inoculación con las cepas Zac.-2 y Zac.-19, que las plántulas de *E. globulus*.

Palabras clave: *Crecimiento de plántulas, distribución de biomasa, área foliar, micorrizas, Eucalyptus.*

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SUMMARY

In order to evaluate the effect of vesicular-arbuscular mycorrhiza (VA) on the initial growth and biomass allocation of *E. camaldulensis* and *E. globulus*, seedlings of these species were inoculated with four VA mycorrhizal isolates (*Glomus* sp. Zac.-2, *Glomus* sp. Zac.-19, *Glomus intraradix* Ex. and *Glomus aggregatum*). Inoculated plants were compared with non inoculated plants, during a 15 week period. Seedlings inoculated with *Glomus* sp. (isolates Zac.-2 and Zac.-19) showed the highest response in height gain (37 %) and biomass production (35 %) as compared to the controls, even though they had the lowest root colonization percentage of all inoculated seedlings. On the other hand, *G. aggregatum* isolate produced the largest root colonization percentage but the lowest effect on seedling growth. Seedlings inoculated with Zac.-2 and Zac.-19 isolates had a shoot:root (17 %) higher than the control, probably due to a higher efficiency for water absorption of the root system. Seedlings of *E. camaldulensis* showed a better response to the inoculation to Zac.-2 and Zac.-19, than seedlings of *E. globulus*.

Index words: *Seedling growth, biomass allocation, foliar area, mycorrhiza, Eucalyptus.*

INTRODUCCION

El género *Eucalyptus* goza de una gran popularidad para el establecimiento de plantaciones comerciales debido a que cuenta con un gran número de especies de rápido crecimiento, con amplio potencial adaptativo y una gran variedad de usos (FAO, 1981; Schopmeyer, 1974). Muchas especies de este género productoras de madera se han plantado extensivamente en programas de reforestación (Malajczuk y Hartney, 1986), destinadas a la obtención de productos de madera, pulpa o combustible, además de una serie de usos indirectos de tipo ambiental y ornamental (FAO, 1981).

La calidad fisiológica de las plántulas producidas en el vivero es de gran importancia para su sobrevivencia y desarrollo después de su estableci-miento en campo. La micorrización es una de las características que pueden influir sobre la calidad de la planta al modificar su patrón de crecimiento y distribución de biomasa. El género *Eucalyptus* es capaz de formar los dos tipos de micorrizas más comunes, las endomicorrizas arbusculares (VA) y las ectomicorrizas (ECM) (Harley y Smith, 1983; Malajczuk *et al.*, 1981; Michelsen, 1992; Molina y Trappe, 1984; Perry *et al.*, 1992).

Las prácticas de inoculación con hongos endomicorrízicos a especies de *Eucalyptus* en vivero son recientes, por lo que existen pocos datos sobre el desarrollo de las micorrizas y del crecimiento de las plántulas de eucalipto en tales condiciones (Burgess *et al.*, 1993; Grove y Le Tacon, 1993). Además, la mayoría de las investigaciones sobre micorrización de especies de eucalipto se han enfocado a ectomicorrizas, y se ha observado que la inoculación con estos hongos es benéfica para las plántulas de eucalipto en varias regiones del mundo (Garbaye *et al.*, 1988; Grove y Le Tacon, 1993). Sin embargo, no existen suficientes evidencias sobre la respuesta de estas plántulas a la inoculación con hongos endomicorrízicos. En virtud de lo anterior, el presente trabajo se hizo con el objetivo de evaluar el efecto de cuatro cepas de hongos endomicorrízicos en el crecimiento inicial y distribu-ción de biomasa en plántulas de dos especies de eucalipto.

MATERIALES Y METODOS

Material Biológico

El estudio se estableció en 1994 en el invernadero de la Sección de Microbiología de la Especialidad de Edafología del Colegio de Postgraduados, en Montecillo, Edo. de México, a una altitud de 2240 m, cuya temperatura y precipitación media anual son de 16 °C y 600 mm, respectivamente. Se utilizó germo-plasma de *E. camaldulensis*, colectado en 1993 en la plantación de San Camilo, Tequesquinahuac, Edo. de México, y de *E. globulus*, colectado en el mismo año en el paraje La Venta, Edo. de México, ubicado sobre la carretera libre México-Veracruz.

Los hongos endomicorrízicos inoculados fueron *Glomus* sp. (Zac.-2 y Zac.-19), *G. intraradix* Extranjera y *G. aggregatum*, a partir de cepas cultivadas en el laboratorio de la citada Sección de Microbiología.

Producción de Planta e Inoculación

La germinación de semillas de las dos especies de eucalipto se llevó a cabo en charolas de plástico, en un sustrato de arena de río y agrolita en una proporción 1:1 (en volumen), previamente esterilizado. La siembra se hizo al voleo el 11 de marzo de 1994, y 25 días después de la germinación las plántulas resultantes se trasplantaron a envases de polietileno negro de 30 cm de largo y 10 cm de diámetro, con un sustrato compuesto de arena y tierra de monte (en proporción 1:1, en volumen), previamente fumigado con bromuro de metilo.

En el momento del trasplante, se llevó a cabo la inoculación de los hongos endomicorrízicos. Para ello, en cada envase se colocaron 10 g de inóculo, consistente en fragmentos de raíz colonizados (>50 %) y esporas contenidas en arena (100 esporas g^{-1}), en la base del sistema radical de las plántulas de eucalipto. Los tratamientos se distribuyeron de acuerdo con un diseño factorial (2 x 5) con un arreglo en bloques completos al azar, con cuatro repeticiones. Cada parcela experimental consistió de 15 plántulas.

Variables Evaluadas

Crecimiento y acumulación de biomasa. En el momento de la inoculación, se seleccionaron al azar y se marcaron cinco plántulas por parcela experimental. En cada una de éstas se midió, periódicamente, el crecimiento en altura y el número de hojas formadas, a intervalos de dos semanas, hasta 15 semanas después de la inoculación. La altura se midió con una regla graduada, con aproximación de mm, desde el cuello de la raíz hasta la yema apical, usando como referencia una línea trazada con pintura roja en la base de la planta en el momento de la primera medición. Para determinar el número de hojas generadas, entre una medición y otra, se colocaron marcas de pintura en la hoja más reciente de las plántulas, en cada fecha de medición.

Al final de las 15 semanas, se cosecharon las cinco plántulas identificadas por parcela para determinar las siguientes características morfológicas: diámetro del tallo, altura final, longitud de la raíz principal, volumen total del sistema radical, área foliar, y acumulación y distribución de biomasa.
El volumen de la raíz se midió con base en el volumen desplazado al sumergirla en una probeta con un volumen conocido de agua. El área foliar se midió con un integrador electrónico 3000A LI-COR (Inc.). Los componentes de biomasa de cada planta (tallo, raíz y hojas) se colocaron en sobres de papel, previamente identificados, para ser secados en un horno a 70 °C durante 72 horas, y luego pesados en una balanza analítica.
Con los promedios de área foliar y biomasa de las cinco plántulas, se estimó el área foliar específica (área foliar/peso seco de hojas) y la relación parte aérea/raíz, en cada parcela.

Colonización micorrízica. El porcentaje de colonización de las cepas endomicorrízicas se evaluó en tres plántulas por parcela, seleccionadas al azar. De cada una de estas plántulas se separó una muestra del sistema radical a la que se aplicó la técnica de clareo y tinción desarrollada por Phillips y Hayman (Jean y Ferrera-Cerrato, 1989). Luego, de cada muestra se seleccionaron 25 raíces y se montaron en un porta objetos, para hacer observaciones en un microscopio óptico con el objetivo 100X. Se hicieron recorridos transversales por segmento, para un total de 75 lecturas por muestra, con el fin de cuantificar la presencia de arbúsculos, vesículas y micelio. El porcentaje de colonización en la raíz se estimó con base en el número de segmentos que mostraron las estructuras mencionadas anteriormente, con respecto al total de segmentos observados al microscopio.

Análisis Estadístico

Con los promedios por parcela se hicieron análisis de varianza en cada variable registrada. El número de hojas y el porcentaje de colonización fueron previamente transformados mediante la función ($\sqrt{X+1}$) y arco seno, respectivamente. Cuando se encontraron diferencias significativas ($P \leq 0.05$) entre los niveles de los factores en estudio, se realizó la prueba de comparación de medias de Tukey.

RESULTADOS Y DISCUSION

Crecimiento de la Planta

Se encontró que durante las primeras ocho semanas, las plántulas no inoculadas de las dos especies de eucalipto superaron en altura y en cantidad de nuevas hojas a las plántulas inoculadas con las cepas endomicorrízicas. Sin embargo, a partir de las 10 semanas, se hizo notorio el efecto positivo de la endomicorrización de algunas cepas sobre el crecimiento del tallo (Figura 1 y 2). Dicho efecto

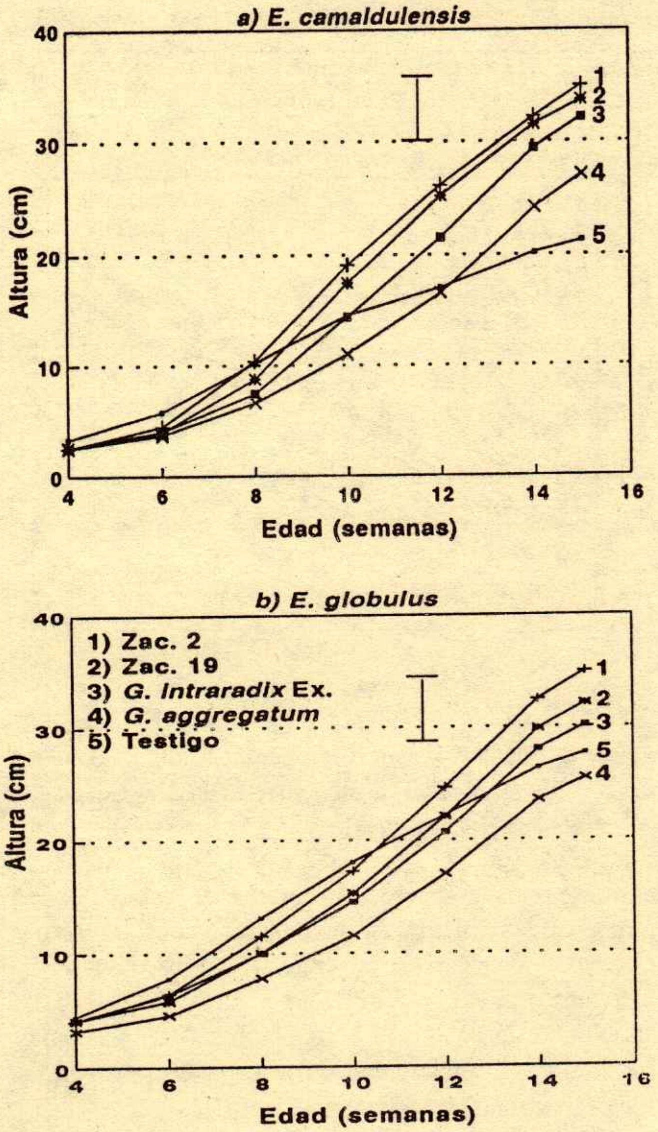

Figura 1. Altura de plantas de (a) *E. camaldulensis* y (b) *E. globulus*, a diferentes edades después de la inoculación con cepas micorrízicas.

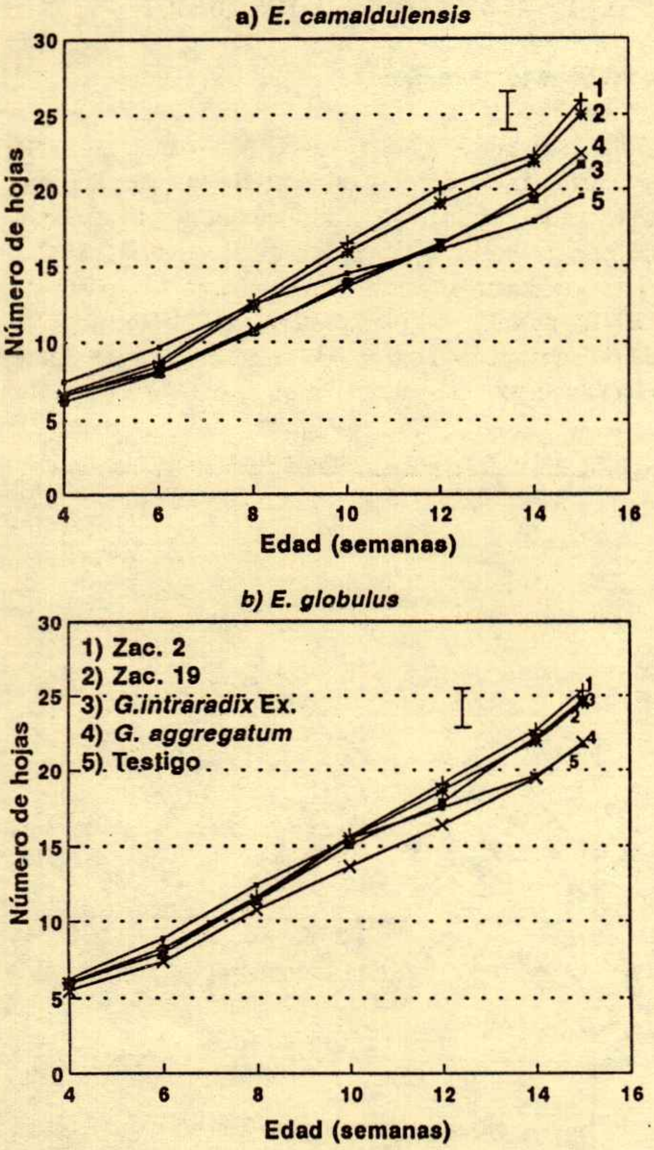

Figura 2. Número de hojas de plantas de (a) *E. camaldulensis* y (b) *E. globulus*, a diferentes edades, después de la inoculación con cepas micorrízicas.

aumentó con el tiempo, al grado de que a las 15 semanas las plántulas inoculadas con las cepas *Glomus* sp. Zac.-2 y Zac.-19 presentaban un incremento de 43 % y 31 % en altura y de 25 y 21 % en número de hojas sobre las plántulas no inoculadas. En cambio, la efectividad de la cepa *G. aggregatum* fue prácticamente nula.

Si bien, en el lapso de 15 semanas, no hubo significancia estadística de la interacción cepa X especie en estas dos características del crecimiento, es de destacarse que en las plántulas de *E. camaldulensis* inoculadas con las dos mejores cepas (Zac.-2 y Zac.-19), el aumento promedio en altura fue de 38 % con respecto a las no inoculadas, mientras que en *E. globulus* el aumento sólo fue de 17 %.

Considerando que el alargamiento del tallo en las dos especies de eucalipto estuvo estrechamente asociado con el número de nuevas hojas (r=0.99), el efecto de las cepas micorrízicas se atribuye, fundamentalmente, a la mejoría en la tasa de formación del follaje, más que al alargamiento de los entrenudos. En otros trabajos también se ha encontrado que la inoculación con hongos endomicorrízicos promueve una mayor altura de las plántulas (Aziz y Sylvia, 1991; De Lucena *et al.*, 1991; Furlan *et al.*, 1983; Kormanik *et al.*, 1981) y un mayor desarrollo de follaje (Kough *et al.*, 1985) en diferentes especies arbóreas, pero en ellas no se ha especificado la correlación que aquí se indica.

Las cepas endomicorrízicas, con excepción de *G. aggregatum,* también ocasionaron un mayor crecimiento en las plántulas de eucalipto, en lo que respecta al diámetro del tallo, área foliar y volumen de raíz (Cuadro 1), y biomasa acumulada en hojas, tallo y raíz, que las plántulas no inoculadas (Figura 3). La superioridad de las plántulas inoculadas con las cepas de *Glomus* sp. (Zac.-2 y Zac.-19) sobre las no inoculadas fluctuó desde 10 % (longitud de raíz) hasta alrededor de 70 % (área foliar y volumen de raíz), siendo de 35 % el incremento promedio en el peso seco total.

Debido al efecto diferencial que tuvo la micorrización en la parte aérea y en la raíz, la relación parte aérea/raíz aumentó significativamente (17 %) en las plántulas inoculadas con las cepas Zac.-2 y Zac.-19, con respecto a las plántulas no inoculadas (Cuadro 1). El área foliar específica, también, aumentó significativamente en más de 25 % en las plántulas inoculadas con estas cepas (Cuadro 1). Un aumento en la biomasa total, asociado con una mayor proporción parte aérea/raíz, sugiere que las plántulas micorrizadas necesitan una menor inversión de nutrimentos en la raíz, además de ser más eficientes en la absorción de agua y nutrimentos. En contraste con las otras cepas endomicorrízicas, *G. aggregatum* indujo un ligero aumento en la proporción de biomasa asignada a la raíz, a expensas de una reducción en la biomasa del follaje, especialmente en *E. camaldulensis* (Figura 3).

En cuanto a la producción y distribución de biomasa en plántulas de eucalipto, el efecto de la

Cuadro 1. Valores promedio por cepa de las variables de crecimiento y producción de biomasa en plántulas de *Eucalyptus*, a 15 semanas de haberse inoculado con diferentes cepas micorrízicas.

Variable	Cepa				
	Zac.-2	Zac.-19	*G. intraradix*	*G. aggregatum*	Testigo
Diámetro del tallo (mm)	2.04 a	1.92 ab	1.82 abc	1.57 c	1.64 bc
Longitud de raíz (cm)	36.71 a	36.58 a	34.18 a	31.70 a	33.40 a
Volumen de raíz (cm^3)	1.98 a	1.96 a	1.29 ab	1.47 ab	1.10 b
Area foliar (cm^2)	141.62 a	138.37 a	116.51 ab	89.67 bc	82.94 c
AF específica (cm^2 g^{-1})	250.15 a	254.20 a	278.29 a	276.26 a	197.05 b
PA/R (g g^{-1})	2.63 ab	3.00 a	2.95 a	2.17 b	2.40 ab

Nota: Valores en una misma línea seguidos por la misma letra no son significativamente diferentes ($P \leq 0.05$).
PA = parte aérea; R = raíz.

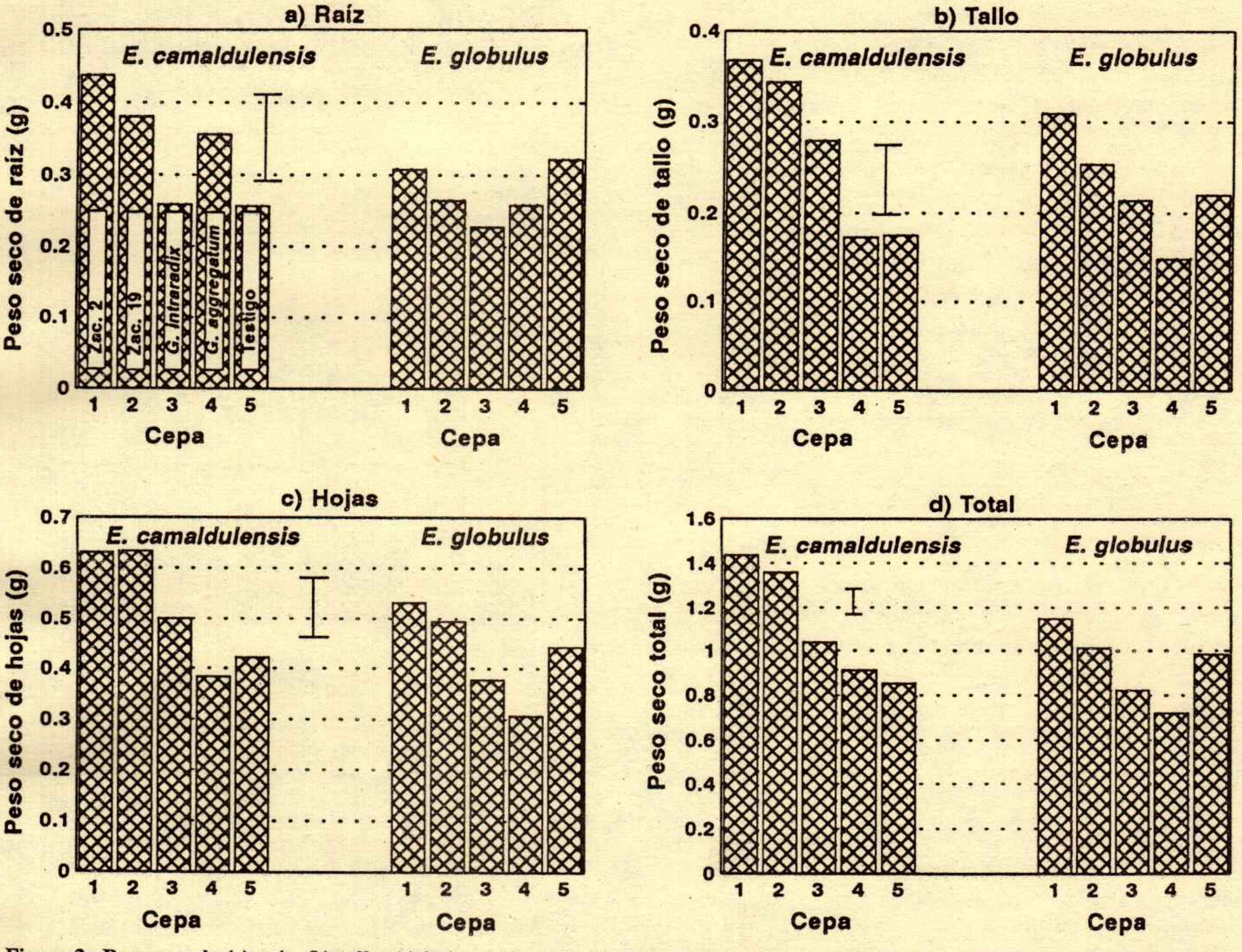

Figura 3. Peso seco de (a) raíz, (b) tallo, (c) hojas y (d) total, en *E. camaldulensis* y *E. globulus* a 15 semanas de haberse inoculado con cuatro cepas endomicorrízicas.

micorrización fue similar al encontrado en otras especies. Por ejemplo, Aziz y Sylvia (1991) encontraron que plántulas de *Leucaena leucocephala* inoculadas con hongos endomicorrízicos presentaron mayores valores en altura, longitud de la raíz y área foliar y una mayor relación parte aérea/raíz que las plántulas no inoculadas. De la misma manera, Dosskey *et al.* (1992) mencionan que la micorrización indujo, como consecuencia, cambios en la distribución de biomasa, frecuentemente reduciendo la proporción de ésta en el sistema radical. Sin embargo, en otros estudios se ha informado que la biomasa de la raíz puede crecer más que la de la parte aérea, ocasionando una reducción en la relación parte aérea/raíz (Ellis *et al*., 1985).

El efecto relativo de las cepas endomicorrízicas también varió de una especie a otra, en lo que se refiere a la acumulación y distribución de biomasa de las plántulas, a 15 semanas de edad (Figura 3). El caso más notorio fue en la biomasa de la raíz de *E. camaldulensis* en donde las cepas de *Glomus* sp. (Zac.-2 y Zac.-19) produjeron un aumento de 41 % y 32 % con respecto al testigo; mientras que en *E. globulus* ninguna de estas cepas superó al testigo (Figura 3). En menor escala, estas diferencias relativas también se observaron en el peso seco del tallo y del follaje, en los que las cepas referidas provocaron un incremento de 51 % y 33 %, respectivamente, en *E. camaldulensis*, pero sólo de 38 % y 18 % en *E. globulus* (Figura 3). Así, las cepas Zac.-2 y Zac.-19 promovieron un incremento promedio de 63 % en la biomasa total de las plántulas en *E. camaldulensis*, mientras que en *E. globulus* el incremento fue menor que 10 %, con respecto a las plántulas no inoculadas (Figura 3).

Colonización Micorrízica

La cepa *G. aggregatum* presentó los mayores valores promedio en la formación de arbúsculos, vesículas y colonización total del sistema radical en las plántulas de eucalipto, mientras que las cepas Zac.-2 y Zac.-19 tuvieron los menores valores de infección (Figura 4). En promedio, las cepas Zac.-2 y Zac.-19 representaron solamente de 30 a 40 % de los arbúsculos y vesículas formados por la cepa *G. aggregatum*, y sólo 60 % de la colonización total realizada por esta cepa (Figura 4). Como era de esperarse, en las plántulas no inoculadas no se observó la formación de estructuras endomicorrízicas.

Nótese que las cepas Zac.-2 y Zac.-19, aunque tuvieron el menor grado de colonización fueron las que estimularon en mayor grado el crecimiento de las plántulas de eucalipto, mientras que la cepa *G. aggregatum* logró mayor colonización, pero causó la menor alteración del crecimiento y distribución de biomasa de las plántulas de eucalipto. Lo anterior

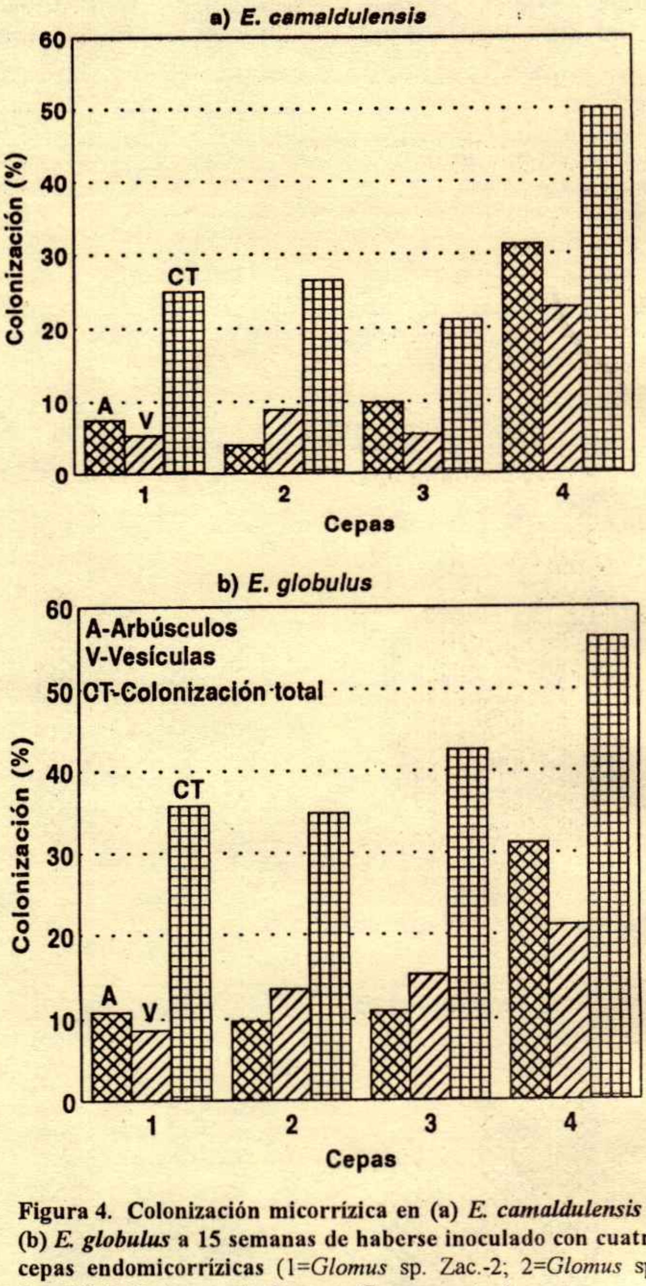

Figura 4. Colonización micorrízica en (a) *E. camaldulensis* y (b) *E. globulus* a 15 semanas de haberse inoculado con cuatro cepas endomicorrízicas (1=*Glomus* sp. Zac.-2; 2=*Glomus* sp. Zac.-19; 3=*G. intraradix* Ex.; y 4=*G. aggregatum*).

parece indicar que hay una relación inversa entre el grado de colonización de las cepas micorrízicas y la respuesta de las plántulas. Estudios realizados por Plenchette *et al*. (1982), Furlan *et al*. (1983) y Palacios *et al*. (1987) apoyan estos resultados, pues encontraron que cepas con bajos valores de colonización indujeron mayor crecimiento en plántulas de *Fraxinus americana* y *Allium cepa* L. que cepas con una mayor colonización. Thompson *et al*. (1994) encontraron respuestas similares a éstas en plántulas de *E. globulus* inoculadas con diferentes cepas ectomicorrízicas.

Eucalyptus globulus presentó valores ligeramente mayores de colonización micorrízica que *E. camaldulensis*; diferencias que fueron significativas ($P \leq 0.05$) en el porcentaje de vesículas y en colonización total. El mayor grado de colonización del sistema radical de *E. globulus* fue consistente en todas las cepas endomicorrízicas empleadas, aunque las diferencias relativas con *E. camaldulensis* son ligeramente mayores en el caso de las cepas Zac.-2, Zac.-19 y *G. intraradix* Ex. (Figura 4). Al evaluar la respuesta, según el crecimiento en dos especies de *Acacia*, a la inoculación con diferentes hongos endomicorrízicos, Michelsen (1993) observó que la respuesta varió de una especie a otra, a pesar del alto grado de colonización observada en ambas especies. De Lucena *et al.* (1991), trabajando con ocho diferentes cepas endomicorrízicas, también encontraron una gran variación en la efectividad de las mismas para lograr la colonización y estimular el crecimiento en plántulas de *Leucaena leucocephala*. En dicho estudio se concluyó que la eficiencia de las cepas está relacionada con la planta hospedera.

CONCLUSIONES

Los resultados del presente trabajo permiten establecer las siguientes conclusiones:

1. La endomicorriza aumentó significativamente el crecimiento en altura, la producción de follaje y de biomasa, y modificó la distribución de ésta en las plántulas de eucalipto. En el caso de la altura y la producción de follaje, el efecto positivo de la micorrización se observó a partir de 10 semanas después de la inoculación, y aumentó gradualmente hasta las 15 semanas.
2. Las cepas endomicorrízicas que promovieron los mayores incrementos en el crecimiento fueron Zac.-2 y Zac.-19 (*Glomus* sp.), a pesar de que éstas indujeron un menor grado de colonización radical que las otras cepas. Por tanto, se infiere que el efecto de la endomicorriza sobre el crecimiento de las plántulas de eucalipto no depende del grado de colonización.
3. Las plántulas de *E. camaldulensis* respondieron mejor que las de *E. globulus* a la inoculación con *Glomus* sp. (Zac.-2 y Zac.-19), en cuanto a altura, diámetro del tallo, área foliar, peso seco de hojas, peso seco de tallo, peso seco aéreo y peso seco total. Así, en *E. camaldulensis* estas cepas promovieron un incremento promedio de 63.5 % en biomasa total con respecto a las plántulas no inoculadas, mientras que en *E. globulus* el incremento promedio fue de sólo 10 %.

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EFICIENCIA AGRONOMICA DE SUPERFOSFATO TRIPLE Y ROCA FOSFORICA EN VARIEDADES DE TRIGO UTILIZANDO EL METODO DE DILUCION ISOTOPICA
I. PARAMETROS AGRONOMICOS

Agronomic Effectiveness of Triple Superphosphate and Rock Phosphate in Wheat Genotypes using the Isotopic Dilution Method
I. Agronomic Parameters

M. Navia[1], W. Luzio[2], I. Pino[3] y A. M. Parada[3]

RESUMEN

La introducción de variedades adaptadas a las condiciones de la zona de suelos volcánicos en Chile, se ha considerado como una estrategia para el desarrollo de una agricultura sostenible, conjuntamente con ello, la existencia de yacimientos de roca fosfórica en el país permitiría la utilización de una fuente alternativa de fósforo para estas nuevas variedades. Por ello, se estableció un ensayo en invernadero para determinar la eficiencia en la absorción y utilización de fósforo en doce variedades de trigo (*Triticum aestivum* L., *Triticum durum*) y evaluar la eficiencia agronómica de superfosfato triple (SFT) y roca fosfórica de Bahía Inglesa (RBI) utilizando parámetros convencionales e isotópicos. Las variables consideradas fueron: materia seca (parte aérea y radical), P absorbido (parte aérea y radical) y eficiencia fisiológica de utilización de P (EFUP). El suelo utilizado fue un Medial, Thermic, Typic Haploxerand (serie Santa Bárbara). Se determinaron diferencias estadísticamente significativas entre las variedades de trigo para los parámetros evaluados, independientemente de las fuentes de P evaluadas. Las variedades con los rendimientos más altos en materia seca (MS) y P absorbido, no fueron necesariamente las más eficientes en la utilización del P absorbido.

Palabras clave: *Roca fosfórica, variedades de trigo, método de dilución isotópica.*

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SUMMARY

On one hand, the introduction of new genotypes adapted to soils of the volcanic region of Chile has been considered as a good strategy to promote sustainable agriculture. On the other hand, important deposits of rock phosphate in Chile would allow the use of an alternative source of phosphorus for these new genotypes. Thus, a greenhouse trial was performed in an Andisol, Santa Barbara series, in order to determine the efficiency and utilization of phosphorus by 12 wheat genotypes (*Triticum aestivum* L., *Triticum durum*), and evaluate the agronomic effectiveness of triple superphosphate (TSP) and Bahía Inglesa rock phosphate (RBI), using conventional and isotopic parameters. The parameters utilized were: dry matter (DM), absorbed phosphorus (P), and physiological utilization efficiency of P (PUEP). Major differences among the cultivars tested were obtained for all the parameters evaluated. The genotypes differences were statistically significant regardless of the P nutrient source under study. Cultivars with the highest DM yield and P absorption were not necessarily the most efficient ones in the utilization of absorbed P.

Index words: *Rock phosphate, wheat genotypes, isotopic dilution method.*

INTRODUCCION

En los suelos volcánicos de Chile, la eficiencia de uso del fósforo aplicado como fertilizante en trigo, en condiciones de campo, varía entre 2 y 8 %, el resto queda retenido en el suelo y no está disponible para la planta. Debido a su alta capacidad de retención de fósforo requieren un mayor suministro de este elemento para mantener una adecuada producción en el cultivo de trigo, con dosis de hasta 400 kg de P_2O_5 ha^{-1} (Montenegro, 1987; Pino *et al.*, 1994). Por otra parte, en Chile existe la posibilidad de utilizar como fuentes de fósforo los depósitos de roca fosfórica natural, cuya explotación y producción permitiría su uso en la agricultura, con el consiguiente ahorro de divisas. El fósforo mineral en estas rocas fosfóricas, las cuales contienen calcio y microelementos, está mayormente en la forma de apatita.

Muchos investigadores, quienes utilizan métodos convencionales e isotópicos, se han dedicado a la evaluación de estos materiales como fuentes de fósforo, considerando su aplicación en forma directa, especialmente en suelos ácidos (Hellums *et al.*, 1989).

A causa de las características de los suelos derivados de cenizas volcánicas y el elevado costo de la fertilización fosfatada, se considera que las investigaciones para lograr un desarrollo auto-sostenible deberían orientarse hacia la obtención de variedades con una mayor eficiencia de utilización del P absorbido proveniente de la roca fosfórica. Ello conllevaría a una disminución significativa de los costos de producción del cultivo en estos suelos del sur de Chile.

Estos antecedentes ponen de manifiesto la importancia económica de los fertilizantes fosfatados en Chile y, por consiguiente, la conveniencia de que su empleo se realice en forma racional. Por lo tanto, los objetivos de esta investigación fueron evaluar la eficiencia de absorción de P de doce variedades de trigo y el comportamiento del superfosfato triple (SFT) y la roca fosfórica de Bahía Inglesa (RBI), utilizando el método de dilución isotópica con ^{32}P.

MATERIALES Y METODOS

Se realizó un ensayo de invernadero en la Estación Experimental Agronómica Antumapu de la Facultad de Ciencias Agrarias y Forestales, Universidad de Chile. El suelo utilizado era proveniente del horizonte superficial (0 a 20 cm) de un Medial, Thermic, Typic Haploxerand (serie Santa Bárbara) (Rojas, 1996), de la VIII Región de Chile. Las variedades de trigo (*Triticum aestivum* L.; *Triticum durum*) seleccionadas para este estudio se presentan en el Cuadro 1. Ellas se agrupan en cuatro categorías según el hábito de crecimiento, tipo de trigo y ciclo vegetativo.

Cuadro 1. Caracterización de las variedades de trigo seleccionadas para este estudio.

No.	Variedad	Hábito de crecimiento	Tipo trigo	Ciclo vegetativo días
Harinero Primaveral				
1	Lilén	Primaveral precoz	De pan	117
2	Nobo	Primaveral precoz	De pan	105
3	Reihue	Primaveral precoz	De pan	116
4	Saeta	Primaveral precoz	De pan	107
Harinero Alternativo				
5	Maqui	Alternativo precoz	De pan	120
6	Canelo	Alternativo precoz	De pan	149
7	Perquenco	Alternativo normal	De pan	180
8	Peumo	Alternativo normal	De pan	155
Harinero Invernal				
9	Lautaro	Invernal precoz	De pan	122
Candeal Primaveral				
10	Chagual	Primaveral normal	Candeal	105
11	Chonta	Primaveral precoz	Candeal	110
12	Lican	Primaveral precoz	Candeal	111

Fuente: Ramírez *et al.* (1990).

Como fuentes de fósforo se aplicaron la roca fosfórica de Bahía Inglesa (RBI), en dosis de 1000 mg P kg^{-1} (T1), y el superfosfato triple (SFT), en dosis de 250 mg P kg^{-1} (TO), con cinco repeticiones.

El diseño experimental fue de bloques completamente al azar, con arreglo factorial de 2 x 12. Los dos factores fueron fertilizantes fosfatados y las variedades de trigo, sumándose un total de 24 tratamientos. Los resultados se sometieron a análisis de varianza al nivel de 5 % ($P< 0.05$) y se usó la prueba de rango múltiple de Duncan para establecer diferencias significativas entre las medias.

La RBI y los macronutrimentos se aplicaron una semana antes de la siembra, mezclados homogénea-mente con el suelo, y el SFT se aplicó localizado en una banda a cinco centímetros de profundidad en la maceta.

Los siguientes análisis para la caracterización química del suelo se realizaron al inicio del experimento y luego al término del ensayo para los Tratamientos T0 y T1: pH, materia orgánica (MO), P disponible (Olsen), capacidad de retención de P (Blakemore), Al oxalato, Ca intercambiable, N total, K disponible, conductividad eléctrica (CE) (Sadzawka, 1990).

Se utilizaron 120 macetas para el ensayo con fertilizantes marcados (método de dilución isotópica) y 48 macetas para la evaluación de materia seca y fósforo absorbido por raíces.

Después de la siembra (tres plantas por maceta) se aplicó la solución nutritiva de los micronutrimentos y se regó con agua destilada hasta capacidad de campo (33 kPa) por peso. Al estado fenológico de inicio de espigadura, en intervalos de tiempo dependiendo de cada variedad (125 días después de la siembra en promedio), las plantas se cosecharon cortándose a ras del suelo.

Los parámetros agronómicos que se determinaron fueron: P absorbido de la parte aérea y radical, materia seca aérea (MSA) y radical (MSR) y, la eficiencia fisiológica de utilización de P (EFUP). Esta última característica se calculó relacionando la cantidad de materia seca producida por unidad de P absorbido.

El P total en la planta (partes aérea y radical) se determinó por colorimetría (metavanadato de amonio) en un espectrofotómetro (Espectronic 20) a 400 nm y la actividad de ^{32}P con un contador de centelleo líquido Beckman 5000 TD, mediante el efecto Cerenkov.

RESULTADOS Y DISCUSION

Características Químicas del Suelo Santa Bárbara

El análisis de algunas características químicas del suelo utilizado en la investigación se presenta en el Cuadro 2.

Los análisis estadísticos no mostraron diferencias significativas entre el suelo inicial y el Tratamiento T0 para todas las características evaluadas, en cambio, en el Tratamiento T1 se apreciaron incrementos significativos en el pH, Ca intercambiable y P disponible, así como una disminución del Al (oxalato), lo que se explicaría por la disolución de la RBI. Similares resultados obtuvieron Krannitz *et al.*(1991) y Sikora (1993).

Materia Seca de la Parte Aérea

Los resultados de rendimientos promedios de materia seca de la parte aérea y radical de la planta para los Tratamientos T0 y T1 se observan en el Cuadro 3.

Los análisis de varianza de materia seca aérea (MSA) reportan diferencias significativas al comparar las dos fuentes estudiadas. Estas diferencias indican que los rendimientos en MSA fueron siempre superiores en los tratamientos en que se adicionó la RBI (T1) comparados con SFT (T0); a excepción de la variedad Lautaro (Harinero Invernal) que fue ligeramente inferior.

En general, se observa que para ambos tratamientos las respuestas en MSA son similares, presentándose con rendimientos altos las variedades Harinero Primaveral (1, Lilén; 2, Nobo; 3, Reihue; y 4, Saeta) y Candeal Primaveral (10, Chagual; 11, Chonta; y 12, Licán) y con rendimientos más bajos los genotipos 6, Canelo; 8, Peumo, y 9, Lautaro; lo cual explicaría porque las variedades Harinero Alternativo presentan una dualidad en el comportamiento, como primaverales o también como invernales (Benitez, 1983). La aplicación de RBI prácticamente no produjo incrementos significativos en el rendimiento

Cuadro 2. Algunas características químicas del suelo Typic Haploxerand (serie Santa Bárbara) y el efecto de los Tratamientos T0 y T1 (valores promedios).

Suelo	pH	Ca_{interc}	P-Olsen	Retenc-P	Al_{oxa}	Conductividad eléctrica
		cmol kg^{-1}	mg kg^{-1}	- - - - %	- - - -	dS m^{-1}
Inicial	6.0 b	4.0 b	8.0 b	97.0 a	5.7 a	0.20 b
T0	5.9 b	4.3 b	9.0 b	94.5 a	5.1 a	1.16 b
T1	6.9 a	16.3 a	12.0 a	95.5 a	2.0 b	1.89 a

* Letras distintas señalan diferencias significativas para las columnas (P<0.05).
T0 = Superfosfato triple, 250 mg P kg^{-1}; T1 = Roca fosfórica, 1000 mg P kg^{-1}.

Cuadro 3. Valores medios de rendimiento de materia seca aérea y radical.

Variedad	T0		T1	
	Materia seca			
	Aérea	Radical	Aérea	Radical
	- - - - - - - - - - g $maceta^{-1}$	- - - - - - - - - -		
Harinero Primaveral				
1 Lilén	5.33 b	1.48 ab	7.98 ab	2.23 bc
2 Nobo	5.64 b	1.37 ab	7.99 ab	2.01 bc
3 Reihue	5.39 b	1.63 ab	7.29 ab	2.25 bc
4 Saeta	5.82 b	1.40 ab	8.86 a	2.44 b
Harinero Alternativo				
5 Maqui	6.26 a	1.56 ab	8.19 ab	2.48 b
6 Canelo	3.30 b	1.11 bc	4.00 ef	1.23 g
7 Perquenco	4.75 bc	1.62 ab	5.64 de	2.92 a
8 Peumo	2.70 e	0.95 d	3.00 f	1.17 g
Harinero Invernal				
9 Lautaro	3.68 cd	0.75 d	3.43 f	1.74 de
Candeal Primaveral				
10 Chagual	5.17 b	1.71 a	5.97 cd	1.90 cd
11 Chonta	4.65 bc	1.01 cd	6.67 cd	1.56 de
12 Lican	4.25 c	1.12 bc	5.47 de	1.38 ef

* Letras distintas señalan diferencias significativas entre las variedades para las columnas (P<0.05).
T0 = Superfosfato triple, 250 mg P kg^{-1}; T1 = Roca fosfórica, 1000 mg P kg^{-1}.

de MSA en las variedades 6, Canelo; 8, Peumo; y 9, Lautaro; similares resultados fueron obtenidos con la aplicación de SFT (T0).

Materia Seca de la Parte Radical

Los incrementos en rendimiento de materia seca radical (MSR), por efecto de la adición de RBI y SFT, fueron estadísticamente significativos para algunas variedades, lo que demuestra una variabilidad moderada en la respuesta de los genotipos.

El rendimiento de MSR representa en promedio 20 % de la MSA de la planta (T0 y T1). Con el Tratamiento T0 se apreció una tendencia similar a la observada en la parte aérea con valores bajos en las variedades 8, Peumo, y 9, Lautaro, y muy similares entre las restantes, siendo el valor más alto el de la variedad 10, Chagual.

En el Tratamiento T1, los menores valores de rendimiento de MSR lo presentaron las variedades 6, Canelo; 8, Peumo; y 12, Lican y el valor más alto fue para la variedad 7, Perquenco.

El efecto de la adición de RBI sobre la MSR se explica por la neutralización del Al^{3+} y la consiguiente disminución de la toxicidad de aluminio soluble sobre el desarrollo radicular (Sikora, 1993). Este desarrollo de la raíz permite explorar un mayor volumen de suelo y, en consecuencia, una mayor disponibilidad de P que se traduce en un rendimiento de MSA más alto. Estos resultados confirman los obtenidos por otros investigadores como Bellott y Navia (1990) y Villarroel y Navia (1989) en maíz, en relación con la existencia de una amplia variación genética en la respuesta a producción de materia seca.

En las variedades 4, Saeta; 5, Maqui; 7, Perquenco; y 9, Lautaro, la relación MSA/MSR (datos no mostrados) disminuyó en T1 debido al aumento de masa radical. En este tratamiento se observaron incrementos en cuanto a la producción de MSA y MSR; sin embargo, la relación de MSA/MSR se mantuvo constante para el resto de las variedades (1, Lilén; 2, Nobo; 3, Reihue; 10, Chagual; y 12, Lican), lo que indica que no hubo cambios en el desarrollo radical por efecto de la aplicación de fertilizantes. Este hecho se refleja en una absorción de P más baja por unidad de raíz cuando el sistema radical es proporcionalmente mayor que la parte aérea.

Cuadro 4. Valores promedios de fósforo absorbido (aérea y radical).

Variedad	T0		T1	
	Fósforo absorbido			
	Aérea	Radical	Aérea	Radical
	- - - - - - - - - mg P maceta^{-1} - - - - - - - - -			
Harinero Primaveral				
1 Lilén	8.10 ab	1.95 ab	13.51 ab	2.70 bcd
2 Nobo	8.80 a	1.81 ab	14.49 a	2.15 cde
3 Reihue	8.55 a	2.46 a	13.06 ab	3.13 b
4 Saeta	8.83 a	1.64 bc	13.89 a	3.04 bc
Harinero Alternativo				
5 Maqui	9.28 a	1.73 b	13.30 ab	3.00 bc
6 Canelo	6.20 bc	1.39 bc	6.60 c	2.01 ef
7 Perquenco	8.03 ab	2.48 a	10.72 b	4.11 a
8 Peumo	5.90 bc	1.34 bc	6.50 c	1.71 f
Harinero Invernal				
9 Lautaro	5.44 c	0.95 c	5.93 c	2.58 cde
Candeal Primaveral				
10 Chagual	8.58 a	1.76 b	12.36 ab	2.10 de
11 Chonta	7.69 ab	1.31 bc	13.25 ab	2.09 ef
12 Lican	8.26 a	1.29 bc	12.08 ab	2.12 de

* Letras distintas señalan diferencias significativas entre las variedades para las columnas ($P<0.05$).

T0 = Superfosfato triple, 250 mg P kg^{-1}; T1 = Roca fosfórica, 1000 mg P kg^{-1}.

Fósforo Absorbido por la Parte Aérea

En el Cuadro 4 se presentan los valores de P total absorbido en las fracciones aérea y radical por las diferentes variedades. En T0 se aprecia que las Variedades Harinero Primaveral (1, Lilén; 2, Nobo; 3, Reihue; y 4, Saeta) y Candeal Primaveral (10, Chagual; 11, Chonta; y 12, Lican) presentan los valores más altos en promedio. En cambio, en el grupo Harinero Alternativo las variedades 6, Canelo, y 8, Peumo, tuvieron una baja absorción de P con un comportamiento similar a la variedad 9, Lautaro, que corresponde a Harinero Invernal. El Tratamiento T1 presenta, en general, valores más altos de P absorbido como producto de la adición de la roca. Las variedades que responden más efectivamente a la aplicación de RBI son 2, Nobo, y 4, Saeta. Sin embargo, la aplicación de RBI prácticamente no produjo ningún incremento en el P total en la variedad 8, Peumo, y en las variedades 6, Canelo, y 9, Lautaro; lo cual indicaría que estas variedades son poco eficientes. La menor absorción se explicaría debido a que estas variedades tienen un requerimiento bajo de P por sus características propias, lo que conlleva a un escaso desarrollo vegetativo, debido a la gran capacidad que tienen de regular sus requerimientos nutricionales (Krannitz *et al.*, 1991).

Fósforo Absorbido por la Parte Radical

El P absorbido en la parte radical representa 16 %, en promedio, del P total absorbido. Con la aplicación de SFT las variedades con mayor absorción de P son la 3, Reihue, y 7, Perquenco, y el valor más bajo se obtuvo con la variedad 9, Lautaro. Ello puede deberse a una disminución en el volumen radical o bien a una disminución en la actividad radical debido al control fisiológico de la variedad (Morel y Fardeau, 1989). Así, Benitez (1983) señala que las plantas con un sistema radical extenso tienen una menor demanda de P por unidad de raíz comparadas con las plantas con sistemas radicales reducidos.

Con la aplicación de RBI, la menor absorción (Cuadro 4) la presentan las variedades 8, Peumo, y 6, Canelo; la más alta la variedad 7, Perquenco. Esta absorción se explica por un mayor desarrollo radical, a causa del mayor volumen de contacto, donde la variedad 7, Perquenco, tiene el mayor desarrollo radical y una menor relación de MSA/MSR.

EFUP por la Parte Aérea de la Planta

En el Cuadro 5 se presentan los promedios de eficiencia fisiológica de uso de fósforo (EFUP). En T0 se aprecian valores más altos de EFUP producto de la mayor reactividad del P del SFT, que es absorbido rápidamente por las plantas, ya que los cultivos anuales tienen un período corto de máxima absorción. Por lo tanto, el factor intensidad, que es la concentración de fosfatos disponibles en el suelo en estados iniciales de la planta, sería el factor más trascendente en la EFUP (Morel y Fardeau, 1989).

Con el Tratamiento T0 se aprecia que las variedades Harinero Primaveral y Candeal Primaveral presentan los valores más altos. El genotipo 8, Peumo, de los trigos Harinero Alternativo tuvo una baja EFUP. El genotipo 9, Lautaro, es el más eficiente en la utilización del P, lo cual se explicaría por la menor acumulación de P en sus tejidos y por tener un bajo requerimiento de este nutrimento. Esto estaría explicando la gran capacidad que tiene de regular sus requerimientos nutricionales, a pesar que presentó una menor absorción P (Krannitz *et al.*, 1991). Por el contrario, la variedad Maqui presenta un comportamiento completamente diferente.

En T1 se aprecia una disminución de los valores de EFUP en comparación con T0, a excepción de las variedades 4, Saeta; 6, Canelo; y 8, Peumo. Esta disminución se puede explicar por el mayor desarrollo radical y la mayor disponibilidad de P en el suelo (Sikora, 1993), que es absorbido por las plantas en concentración sobre los requerimientos normales y almacenada en sus tejidos. Con la aplicación de roca fosfórica, la mayor eficiencia fisiológica total se aprecia para las variedades 4, Saeta; 5, Maqui; y 6, Canelo, y las menos eficientes fueron 12, Lican; 8, Peumo; y 10, Chagual.

En esta investigación se ha podido determinar que las variedades que presentaron mayor rendimiento de MS (Harinero Primaveral, Candeal Primaveral y las variedades 5, Maqui, y 7, Perquenco, de Harinero Alternativo), no necesariamente fueron las más eficientes en la utilización del P absorbido. Por lo tanto, para las variedades con esta característica no se debería utilizar el nivel de crecimiento como único parámetro de selección. Esto podría inducir a error debido a que fácilmente se puede deducir que las variedades más productivas serían las que presentan la mayor adaptación a bajos contenidos de P. Además, las variedades utilizadas en este estudio presentan ciclos de crecimiento muy diferente que varían desde 105 hasta 180 días. Por consiguiente, se deben esperar diferentes requerimientos de absorción de P con el tiempo.

Cuadro 5. Valores medios de eficiencia fisiológica del uso de fósforo (EFUP).

Variedad	T0		T1	
	Eficiencia fisiológica de uso de P (EFUP)			
	Aérea	Radical	Aérea	Radical
	$g\ mg^{-1}\ P$			
Harinero Primaveral				
1 Lilén	0.66 a	0.76 b	0.59 b	0.83 a
2 Nobo	0.64 a	0.75 b	0.55 b	0.93 a
3 Reihue	0.63 a	0.66 c	0.56 b	0.72 b
4 Saeta	0.46 c	0.85 ab	0.64 a	0.80 a
Harinero Alternativo				
5 Maqui	0.67 a	0.90 a	0.62 a	0.83 a
6 Canelo	0.53 bc	0.80 b	0.61 a	0.64 c
7 Perquenco	0.59 b	0.65 c	0.53 bc	0.71 b
8 Peumo	0.46 c	0.34 d	0.46 c	0.68 c
Harinero Invernal				
9 Lautaro	0.68 a	0.79 b	0.58 b	0.67 c
Candeal Primaveral				
10 Chagual	0.60 ab	0.97 a	0.48 c	0.90 a
11 Chonta	0.60 ab	0.77 b	0.50 bc	0.78 b
12 Lican	0.51 bc	0.87 ab	0.45 c	0.65 c

* Letras distintas señalan diferencias significativas entre las variedades para las columnas ($P<0.05$).

T0 = Superfosfato triple, 250 mg P kg^{-1}; T1 = Roca fosfórica, 1000 mg P kg^{-1}.

EFUP de la Parte Radical de la Planta

Con la adición de RBI las variedades que disminuyeron su EFUP fueron 4, Saeta; 5, Maqui; 6, Canelo; 9, Lautaro; 10, Chagual; y 12, Lican, esto indicaría que esas variedades no son eficientes. Las variedades que respondieron más efectivamente a la aplicación de la RBI fueron 1, Lilén; 2, Nobo; 3. Reihue; 7, Perquenco; y 8, Peumo. La adición de la RBI no afectó en lo absoluto a la variedad 11. Chonta en la EFUP, a pesar de tener una disminución en la relación de MSA/MSR.

Las variaciones en la eficiencia fisiológica de uso de P se explicaría en términos de diferencias en los mecanismos fisiológicos y bioquímicos de absorción y utilización de P específicos para cada variedad. Esto produciría, de alguna forma, variaciones en la translocación de este nutrimento hacia el follaje. Al parecer las variedades más eficientes en la utilización de P tendrían una gran habilidad de translocar y retranslocar este elemento desde tejidos inactivos hacia tejidos activos (Trought, 1982).

CONCLUSIONES

1) Las variedades de trigo en estudio presentaron diferencias significativas en la eficiencia de absorción de P, independientemente de las fuentes de P evaluadas (SFT y RBI). Dicho parámetro está más asociado a las características genéticas y fisiológicas de los cultivares que a las condiciones del medio.

2) Las variedades con los rendimientos más altos en MS y P absorbido no fueron las más eficientes en la utilización de P. Ello significa que las variedades más productivas no son necesariamente las mejores adaptadas a condiciones de baja disponibilidad de P, situación que ocurre comúnmente en las condiciones estudiadas.

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EFICIENCIA AGRONOMICA DE SUPERFOSFATO TRIPLE Y ROCA FOSFORICA EN VARIEDADES DE TRIGO UTILIZANDO EL METODO DE DILUCION ISOTOPICA.
II. PARAMETROS ISOTOPICOS

Agronomic Effectiveness of Triple Superphosphate and Rock Phosphate in Wheat Genotypes using the Isotopic Dilution Method.
II. Isotopic Parameters

M. Navia[1], I. Pino[2], W. Luzio[3] y A.M. Parada[2]

RESUMEN

La introducción de variedades adaptadas a las condiciones edáficas de la zona de suelos volcánicos en Chile, se ha considerado como una estrategia para el desarrollo de una agricultura sostenible, conjuntamente con ello, la existencia de yacimientos de roca fosfórica en el país permitiría la utilización de una fuente alternativa de fósforo para estas nuevas variedades. Por ello, se realizó un ensayo en invernadero para evaluar la eficiencia agronómica de superfosfato triple (SFT) y roca fosfórica• de Bahía Inglesa (RBI) utilizando el método de dilución isotópica. Se determinó el porcentaje de P en la planta proveniente de SFT (% PddF), el porcentaje de P proveniente del suelo (% PddS) y el porcentaje de P proveniente de la RBI (% PddR); además, se determinó el uso eficiente del SFT (UESFT), de la RBI (UER), y el valor A del suelo (A_s) y de la RBI (A_R). Se encontraron diferencias estadísticamente significativas entre las variedades de trigo para los parámetros evaluados. Las técnicas isotópicas permitieron determinar cuantitativamente las fuentes en estudio, SFT y RBI, incluyendo el P nativo del suelo. El P proveniente de la RBI es bastante bajo, por lo cual se puede concluir que la RBI no constituye una alternativa efectiva como fertilizante fosfatado para suelos derivados de cenizas volcánicas de pH superior a 5.5. Las variedades de trigo presentaron diferencias significativas en la disponibilidad de P en el suelo y de la RBI, lo cual estaría indicando que estos parámetros están asociados a las características genéticas y fisiológicas de los cultivares, debido a que inicialmente dispondrían de la misma cantidad de nutrimento.

Palabras clave: *Roca fosfórica, variedades de trigo, método de dilución isotópica.*

SUMMARY

On one hand, the introduction of new genotypes adapted to the soils of the volcanic region of Chile has been considered as a good strategy to promote sustainable agriculture. On the other hand, important deposits of rock phosphate in Chile would allow the use of an alternative source of P for these new genotypes. Thus, a greenhouse trial was carried out to evaluate the agronomic effectiveness of rock phosphate (RBI) from Bahía Inglesa and triple superphosphate (TSP), through the ^{32}P isotopic dilution method. The parameters measured were P derived from the labeled fertilizer (% PdfF), P derived from the soil (% PdfS) and P derived from the RBI (% PdfR). Great differences among the cultivars tested were obtained for all the evaluated parameters. Isotopic techniques allow to measure the P from TSP and RBI and also P from the soil. The results showed that P from RBI is very low assuming that the RBI is not an effective alternative as phosphorus fertilizer for volcanic ash soils with pH higher than 5.5. The wheat genotypes tested exhibit great differences among them, with regard to availability of P in the soil and from the RBI. This means that both parameters are associated to genetic and physiologic characteristics of genotypes, considering the primary P availability was identical.

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Index words: ***Rock*** *phosphate, wheat genotypes, isotopic dilution method.*

INTRODUCCION

El descubrimiento de yacimiento de apatitas en el norte de Chile plantea el desafío de desarrollar tecnologías y métodos prácticos acordes con la realidad económica nacional, de modo que puedan utilizarse estos minerales, al menos en parte, como fertilizantes fosfatados eficientes. Existe una gran cantidad de apatitas de composición variable, que surgen por sustitución isomórfica de la estructura básica de la apatita. Estas sustituciones pueden ser catiónicas o aniónicas, las principales son: Ca^{2+} sustituido por Mg^{2+}, o Na^+ y PO_4^{3-} sustituidos por CO_3^{2-} o F^-, las que influyen profundamente la estructura cristalina y la estabilidad física y química de la apatita (Reyes, 1987).

A través de numerosas experiencias se ha establecido que la aplicación de rocas fosfóricas en forma directa es más efectiva en suelos ácidos, debido a que las apatitas son más inestables a pH bajos (Khasawneh y Doll, 1978; Kucey y Bole, 1984). También se ha encontrado que los principales factores que afectan la efectividad agronómica de la roca fosfórica en la aplicación directa son las propiedades del suelo, las prácticas de manejo y los cultivos.

Entre los métodos utilizados para la evaluación de la eficiencia agronómica de fuentes fosfatadas, el de dilución isotópica con ^{32}P es uno de los más efectivos para diferenciar en forma cuantitativa el fósforo en la planta proveniente de fuentes como el fósforo disponible en el suelo, el fósforo proveniente de fertilizantes inorgánicos o el fósforo proveniente de compuestos orgánicos. De esta manera se logra determinar el coeficiente real de utilización del P de los fertilizantes. La evaluación agronómica se realiza sobre la base de los parámetros isotópicos de disponibilidad de P o valores A (Pino *et al.*, 1992).

Los objetivos de esta investigación fueron evaluar la eficiencia de SFT y RBI mediante el método de dilución isotópica con ^{32}P, utilizando tanto parámetros agronómicos (Parte I) como isotópicos. En este artículo se obtiene la eficiencia de uso de estas fuentes de P utilizando los parámetros isotópicos.

MATERIALES Y METODOS

Se trabajó con superfosfato triple (SFT) marcado con ^{32}P, con una actividad específica de 0.5 mci g P^{-1} (18.5 MBq g P^{-1}), en una dosis de 250 mg P kg^{-1}. Como fuente no marcada se utilizó roca fosfórica de Bahía Inglesa en dosis de 1000 mg P kg^{-1}.

Para el análisis de ^{32}P en el material vegetal se calcinaron 2 g de muestra seca a 550 °C y se diluyeron en 25 mL. Se tomaron 5 mL de la solución obtenida de la muestra calcinada y se transfirieron a viales plásticos agregando 5 mL de H_2O destilada. Se determinó la actividad específica del isótopo ^{32}P en cada muestra, en un contador de centelleo líquido Beckman 5000 TD, mediante el efecto Cerenkov. El P total en la planta se determinó por colorimetría (metavanadato de amonio) en un espectrofotómetro (Espectronic 20) a 400 nm.

Los parámetros isotópicos evaluados fueron el porcentaje de P en la planta proveniente del SFT (% PddF), el porcentaje de P en la planta proveniente del suelo (% PddS) y el porcentaje de P en la planta proveniente de la RBI (% PddR). Además, se determinó el coeficiente real de utilización del P del SFT (EUSFT) y de la RBI (EUR). También se calcularon los valores A_s y A_r para realizar la evaluación agronómica con estos parámetros isotópicos (Pino *et al.*, 1992; Zapata y Axmann, 1991, 1993).

RESULTADOS Y DISCUSION

Fósforo en la Planta Proveniente del SFT-^{32}P y Fósforo en la Planta Proveniente del Suelo (Tratamiento T0)

En el Cuadro 1, el P en la planta derivado del SFT (% PddF) presenta un comportamiento muy similar en todas las variedades, con porcentajes bastantes altos, en promedio sobre 70 %, lo cual corrobora la baja disponibilidad de P en este suelo, así como su alta capacidad de retención de P, producto de la interacción con alófano y complejos de humus con Fe y Al (Pino, 1986).

Cuadro 1. Fósforo proveniente del superfosfato triple-^{32}P (% PddF) y del suelo (% PddS). Tratamiento T0.

Variedad	PddF	PddS
	------- %	-------
Harinero Primaveral		
1 Lilén	71.1 b	28.9 b
2 Nobo	71.2 b	28.8 b
3 Reihue	73.0 b	26.9 b
4 Saeta	73.1 b	26.9 b
Harinero Alternativo		
5 Maqui	72.6 b	27.4 b
6 Canelo	88.6 a	11.9 c
7 Perquenco	74.8 b	25.2 b
8 Peumo	57.9 c	42.1 a
Harinero Invernal		
9 Lautaro	72.8 b	27.2 b
Candeal Primaveral		
10 Chagual	74.7 b	25.3 b
11 Chonta	70.8 b	29.1 b
12 Lican	71.6 b	28.4 b

* Letras distintas señalan diferencias significativas entre las variedades de trigo para las columnas ($P<0.05$).

Con un valor cercano a 90 % se destaca la variedad 6, Canelo, y con 58 % PddF sólo la variedad 8, Peumo. En general, los porcentajes obtenidos son bastante altos, aun cuando la dosis de P por maceta fue de 250 miligramos. En consecuencia, el porcentaje de P en la planta proveniente del suelo es claramente inferior (Cuadro 1) al P proveniente del fertilizante. El bajo porcentaje de la variedad 8 no puede explicarse por factores de suelo, sino más bien por factores inherentes a la variedad, probablemente por una mayor capacidad de las raíces de extraer el P disponible del suelo, ya que no se observó ni mayor materia seca radical, ni mayor P total en la planta (Parte I).

Los análisis de varianza del % PddS muestran diferencias significativas para las variedades. Realizando comparaciones ortogonales entre los grupos, las diferencias no son significativas, lo que indica que no existe variación entre los grupos de variedades. En cambio, realizando las comparaciones de medias entre las variedades, los trigos Harineros Alternativos muestran diferencias significativas apreciándose la variedad 8, Peumo, con el valor más alto y la variedad 6, Canelo con el menor.

Ello confirma la baja disponibilidad del P del suelo durante el desarrollo de las variedades. Por otra parte, la variedad 8, Peumo, fue capaz de absorber porcentajes similares de P provenientes del fertilizante y del suelo. Sin embargo, esta variedad presentó menor producción de MST, menor P absorbido y menor EFUP (Parte I).

Fosforo en la Planta Proveniente de la RBI, P Proveniente del Suelo y P Proveniente del SFT-^{32}P (Tratamiento T1)

En el Cuadro 2 se muestran los valores de P en la planta proveniente de la RBI (% PddR), del suelo (% PddS) y del fertilizante (% PddF) para el Tratamiento T1. Los análisis de varianza reportaron significancia para las variedades.

Al adicionar RBI, se observó un importante incremento en materia seca (MS) y P total en todas las variedades con respecto al Tratamiento T0 (Parte I). Sin embargo, Zapata y Axmann (1993) señalan que ni la ganancia de MS ni la absorción de P son buenos parámetros para la evaluación de rocas fosfóricas. De ahí, la importancia de evaluar este parámetro a través de técnicas isotópicas, por cuanto el % PddR es independiente del rendimiento y refleja la real utilización de la roca fosfórica. También Pino *et al.* (1992) indican que la utilización de técnicas isotópicas es adecuada para este tipo de estudios y muestra ser eficiente en la evaluación de diferentes materiales fertilizantes portadores de P.

Las variedades capaces de utilizar en mejor forma el P proveniente de la RBI (13 a 20 % PddR), por tanto, más eficientes en su absorción son: 12, Lican; 11, Chonta; y 4, Saeta; y las menos eficientes (0.9 a 1.3 % PddR) son las variedades 5, Maqui; 7, Perquenco; y 8, Peumo, mientras que el resto presentó eficiencias intermedias con valores entre 2.2 y 7.8 %. Esta gran variación en la absorción de P proveniente de la RBI se explicaría por los mecanismos fisiológicos de las variedades o por su habilidad para tolerar la toxicidad del aluminio. Caradus (1983) señala que ello podría deberse a la capacidad que tienen las variedades de regular sus requerimientos nutricionales. Además, el bajo porcentaje de P proveniente de la RBI se podría deber a la menor disolución de la RBI a pH mayor que 5.5.

La mayor o menor absorción de P por un determinado genotipo podría atribuirse a que utilizan diferentes formas de P del suelo. Así podrán diferir en el efecto de la rizósfera en solubilizar o utilizar más P del suelo o del fertilizante (Pino, 1986). Este efecto debería evaluarse desde el punto de vista genético, ya

Cuadro 2. Fósforo en la planta proveniente de la roca fosfórica Bahía Inglesa (% PddR), del fertilizante (% PddF) y del suelo (% Pdds). Tratamiento T1.

Variedad	PddR†	PddS	PddF
	- - - - - - - -	%	- - - - - - - -
Harinero Primaveral			
1 Lilén	2.2 de	30.5 bc	67.3 bc
2 Nobo	7.6 b	34.2 b	58.2 bcd
3 Reihue	2.7 cd	28.9 c	68.4 bc
4 Saeta	13.1 a	36.5 ab	50.4 bcd
Harinero Alternativo			
5 Maqui	0.9 f	28.1 c	70.9 bc
6 Canelo	3.4 c	14.4 d	82.2 a
7 Perquenco	1.0 ef	25.9 cd	73.1 b
8 Peumo	1.3 aef	48.8 a	49.9 e
Harinero Invernal			
9 Lautaro	4.3 c	30.4 bc	65.3 bc
Candeal Primaveral			
10 Chagual	7.8 b	31.1 b	61.1 bc
11 Chonta	15.3 a	39.9 ab	44.7 de
12 Lican	19.6 a	42.4 a	37.9 e

* Letras distintas señalan diferencias significativas entre variedades de trigo para las columnas ($P<0.05$).

† Categorías arbitrarias PddRF para las variedades:

Eficientes	>10 %
Medianamente eficientes	2 a 10 %
No eficientes	< 2 %

que es importante la obtención de variedades que sean eficientes en el uso tanto del P nativo como de aquel aplicado como fertilizante.

Con respecto al % PddS, los análisis de varianza reportan diferencias entre las variedades. También se observa mayor P disponible del suelo que en el caso de sólo aplicar SFT (Cuadro 1) producto de la mineralización de P orgánico por efecto del incremento de pH y Ca intercambiable que disminuyen el Al intercambiable (Krannitz *et al.*, 1991; Sikora, 1993; Wright *et al.*, 1991).

Las variedades que presentaron menores % PddS fueron la 6, Canelo, seguida por las variedades 7, Perquenco; 3, Reihue; y 5, Maqui; los valores más altos fueron aquellos de las variedades 8, Peumo, y 12, Lican.

Al respecto, Pino y Casas (1988) y Pino *et al.* (1992) establecen que se produce una interacción entre el P proveniente de la roca fosfórica y el suelo, de tal manera que a medida que éste se solubiliza se produce simultáneamente una precipitación del mismo, compitiendo con la planta en la disponibilidad de este nutrimento. El % PddS en T0 fue inferior a aquel evaluado en T1, de esta manera se demuestra que el cambio en el pH y en el contenido de Ca intercambiable influye claramente en incrementar la disponibilidad de P del suelo; de esta manera, la aplicación de RBI constituiría una enmienda más que una fertilización. Ello también se corroboró debido a que no hubo una disminución notable de la actividad específica (AE) en los tratamientos con RBI (Zapata y Axmann, 1991). Así, el % PddF para T1 muestra sólo una ligera disminución, lo que evidencia una vez más la baja efectividad de la RBI como fertilizante en este suelo, aun cuando para las variedades 11, Chonta; 2, Nobo; y 8, Peumo, este efecto es más positivo.

Coeficiente Real de Utilización de P de los Fertilizantes

En el Cuadro 3 se presentan los valores promedios de los coeficientes reales de uso de los fertilizantes fosfatados (RBI y SFT). Estos valores indican la medida directa y cuantitativa de la absorción del P del fertilizante por la planta con relación a la cantidad de nutrimento que se agrega al suelo (Zapata y Axmann, 1991). Los análisis de varianza reportan diferencias significativas para las variedades y los grupos de acuerdo con su ciclo vegetativo. Las variedades 8, Peumo, y 12, Lican, presentaron una mayor EURF, seguida de las variedades 11, Chonta; 4, Saeta; 2, Nobo; y 10, Chagual, en forma descendente.

Este parámetro de EURF es bajo para todas las variedades y estaría indicando la ventaja de utilizar SFT por el contenido de P soluble, comparado con la RBI que tiene una lenta solubilidad (Pino y Casas, 1988). El efecto negativo de la capacidad de retención de P también tiene incidencia sobre la RBI, ya que el P que llega a la solución del suelo proveniente de la RBI es susceptible a reaccionar con éste para formar compuestos menos disponibles para las plantas (Pino y Casas, 1988).

La eficiencia real de la RBI fue extremadamente baja, lo que indicaría una vez más el efecto de enmienda de este material y mayor efecto residual, en suelos con alta capacidad de retención de P y con pH superior a 5.5 (Cuadro 3).

Con SFT se aprecia que la variedad 8, Peumo, es la que incrementa en menor proporción la EUSFT (70 %), seguida de la variedad 9, Lautaro, mientras que el resto de variedades incrementaron en proporciones mayores que 90 % con respecto a la EURF.

La eficiencia de uso del SFT (EUSFT) es baja para este tipo de suelo, sin embargo, corresponde a los

Cuadro 3. Coeficiente real de utilización del fósforo de los fertilizantes. Roca fosfórica Bahía Inglesa (RBI) (% UER) y superfosfato triple (SFT) (% UESFT).

Variedad	Coeficientes de utilización del P de los fertilizantes	
	RBI	SFT
	- - - - - %	- - - - -
Harinero Primaveral		
1 Lilén	0.03 cd	2.3 a
2 Nobo	0.11 b	2.5 a
3 Reihue	0.03 cd	2.5 a
4 Saeta	0.18 ab	2.6 a
Harinero Alternativo		
5 Maqui	0.01 d	2.7 a
6 Canelo	0.02 d	2.2 ab
7 Perquenco	0.01 d	2.4 a
8 Peumo	0.32 a	1.1 b
Harinero Invernal		
9 Lautaro	0.03 cd	1.6 b
Candeal Primaveral		
10 Chagual	0.10 b	2.6 a
11 Chonta	0.20 a	2.2 ab
12 Lican	0.24 a	2.4 a

* Letras distintas señalan diferencias significativas entre variedades para las columnas ($P<0.05$).

Cuadro 4. Valores promedio de la disponibilidad de P del suelo (A_s), de la roca fosfórica (A_R) y evaluación agronómica (EA).

Variedad	Valor A_S	Valor A_R	EA
	- - mg P kg^{-1} †	- -	kg kg^{-1} ‡
Harinero Primaveral			
1 Lilén	101.8 b	7.9 b	126.3 a
2 Nobo	101.0 b	28.7 cd	34.8 cd
3 Reihue	92.6 b	9.2 dc	108.6 a
4 Saeta	92.1 b	51.5 b	19.4 d
Harinero Alternativo			
5 Maqui	94.6 b	3.4 e	291.6 a
6 Canelo	32.6 c	10.0 d	99.6 b
7 Perquenco	84.6 b	3.0 e	329.0 a
8 Peumo	187.7 a	98.5 a	10.2 e
Harinero Invernal			
9 Lautaro	93.5 b	15.5 d	64.3 b
Candeal Primaveral			
10 Chagual	84.8 b	28.2 cd	35.5 cd
11 Chonta	102.7 b	63.8 b	15.7 de
12 Lican	99.2 b	85.1 a	11.8 e

* Letras distintas señalan diferencias significativas entre las variedades de trigo para las columnas ($P<0.05$).

† kg^{-1} = peso suelo por maceta.

‡ Clasificación de los valores de EA:
- Alta eficiencia < 15 kg P RF/kg P SFT
- Media eficiencia 16 a 30 kg P RF/kg P SFT
- Baja eficiencia > 31 kg P RF/kg P SFT.

valores obtenidos con otros suelos derivados de cenizas volcánicas (Pino y Casas, 1989; Pino *et al.*, 1994).

Valor "A" del Suelo y Valor "A" de la Roca Fosfórica

En el Cuadro 4 se muestran los valores promedios de la disponibilidad de P del suelo (A_s) y la roca fosfórica (A_R) para las doce variedades de trigo, con la respectiva comparación de medias.

Los análisis de varianza del valor A_s presentaron diferencias significativas para las variedades, constituyendo un ejemplo claro de la diferente capacidad de absorción de cada uno de los genotipos, ya que el suelo es el mismo y, por lo tanto, se esperaría un valor único.

En la variedad 8, Peumo, se apreció el valor más alto de disponibilidad de P del suelo, lo que estaría indicando que tiene 187.7 mg P kg^{-1} como unidades equivalentes de SFT, en tanto la variedad 6, Canelo, es la de menor valor debido a que presentó 32.6 mg P kg^{-1} como unidades equivalentes de SFT.

El análisis de varianza para el valor A_R presentó diferencias significativas, lo que estaría indicando la variabilidad de disponibilidad de P proveniente de la RBI, que se explicaría por los mecanismos genéticos y fisiológicos inherentes a las variedades, ya que dispondrían inicialmente de la misma cantidad de P.

La variedad 8, Peumo, presentó el valor A_R más alto de 98 mg P kg^{-1} como unidades equivalentes de SFT; en cambio, las variedades 5, Maqui, y 7, Perquenco, tienen valores bajos de 3 mg P kg^{-1} como equivalentes de SFT, lo que refleja la baja disponibilidad del P proveniente de la RBI.

Al observar los valores promedios de los grupos, se aprecia que las variedades del grupo Candeal Primaveral son las más eficientes, por tener los valores más altos de A_R; esta superioridad se traduce en 59 % más que el grupo Harinero Primaveral, 51 % más que el grupo Harinero Alternativo y 74 % más que Harinero Invernal. Esto estaría indicando la mayor disponibilidad del P proveniente de la RBI para este grupo de variedades con respecto a los demás.

Evaluación Agronómica de los Fertilizantes Fosfatados en Estudio

La respuesta a la aplicación de 1000 mg de P maceta^{-1} de roca fosfórica difiere entre las variedades.

Así, 1000 mg P como RBI maceta^{-1} provee 98.5 unidades SFT para la variedad 8, Peumo, en tanto que sólo da 3.0 unidades equivalentes de SFT para la variedad 7, Perquenco. Esto significa que el P en el SFT fue 10 veces más disponible en la variedad 8, Peumo, y 329 veces en la variedad 7, Perquenco.

En el Cuadro 4 se presentan los valores promedio correspondientes a la evaluación agronómica expresada en kg de P como RBI equivalentes a 1 kg de P como SFT (kg kg^{-1}) para las variedades de trigo, lo cual permite realizar la evaluación agronómica de la RBI como fuente fosfatada (Zapata y Axmann, 1991).

Las diferencias significativas de las comparaciones ortogonales señalan al grupo Harinero Alternativo con el valor más alto de equivalencia, comparado con el resto de los grupos de variedades. Esta diferencia expresada en porcentaje es 60 % más que el Harinero Primaveral; 65 % más que el grupo Harinero Invernal y 88 % más que Candeal Primaveral. Esto estaría indicando que todas aquellas variedades que tienen alto valor de equivalencia son las menos eficientes en cuanto a la utilización de la roca fosfórica como fuente de P.

Por otra parte, analizando las comparaciones entre las variedades dentro de cada grupo, existen diferencias en el grupo Harinero Primaveral, que clasifica a las variedades 1, Lilén; 3, Reihue; y 2, Nobo, con una eficiencia baja en cuanto al uso de la RBI como fertilizante de P, en cambio, la variedad 4, Saeta, tiene una eficiencia media.

Así mismo, entre las Variedades Harinero Alternativo existen diferencias significativas para las variedades, señalando a la 8, Peumo, como una de las de mayor eficiencia en el uso de RBI que se clasifica como alta, comparada con las variedades 7, Perquenco; 5, Maqui, y 6, Canelo, que son de baja eficiencia. El trigo Harinero Invernal, 9, Lautaro tiene un valor bajo de eficiencia que va acompañada de una menor producción de MS y disminución en la absorción de P, y fue la variedad que presentó un peor comportamiento (Parte I).

La variedad 7, Perquenco, es la menos eficiente en la utilización de la roca fosfórica como fuente fosfatada, debido a que requeriría de 329 kg de P como RBI para igualar a 1 kg de P como SFT, en tanto la variedad 8, Peumo, sólo requiere de 10 kg de P como RBI para igualar a 1 kg de P como SFT, por lo cual se señala que es una de las variedades más eficientes en utilizar la RBI como fuente fosfatada, en el suelo estudiado.

CONCLUSIONES

1) Las técnicas isotópicas permitieron determinar cuantitativamente las fuentes en estudio, SFT y RBI, incluyendo el P nativo del suelo.
2) El P proveniente de la RBI es bastante bajo, por lo cual se puede concluir que la RBI no constituye una alternativa efectiva como fertilizante fosfatado para suelos derivados de cenizas volcánicas de pH superior a 5.5.
3) Las variedades de trigo presentaron diferencias significativas en la disponibilidad de P en el suelo y de la RBI, lo cual estaría indicando que estos parámetros están asociados a las características genéticas y fisiológicas de los cultivares, debido a que inicialmente dispondrían de la misma cantidad de nutrimentos.
4) Los parámetros convencionales sobrestimaron los resultados, en tanto la técnica isotópica demostró ser eficiente, cuantitativa y rápida en la evaluación de los genotipos con respecto a la habilidad para absorber el P liberado a partir de la RBI.

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MODELOS DE RESPUESTA A NITROGENO Y FOSFORO PARA EL TRIGO EN EL VALLE DEL YAQUI, SONORA

Response Models to Nitrogen and Phosphorus for Wheat in the Yaqui Valley, Sonora

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RESUMEN

En este artículo se analizan las recomendaciones de fertilización nitrogenada y fosforada para el cultivo del trigo (*Triticum aestivum* L.) generadas por cuatro modelos de respuesta en el Valle del Yaqui y se proporcionan los programas de cómputo en SAS (Statistical Analysis System) para su ajuste. Para el cálculo de las recomendaciones de fertilización se utilizaron los datos de tres experimentos conducidos con agricultores cooperantes. El rendimiento de grano se modeló con cuatro superficies de respuesta con diferentes niveles de complejidad (modelo cuadrático, cuadrático con plateau, senoidal y exponencial). Aunque el ajuste de estos modelos fue similar al evaluarlos con el criterio de la R^2, se encontraron diferencias marcadas entre el modelo cuadrático con plateau y los otros tres en la predicción de dosis óptimas económicas de nitrógeno. Las dosis óptimas económicas para N variaron de 106 kg ha^{-1} con el modelo cuadrático con plateau a 138 con el modelo senoidal y las de P_2O_5 de 15 kg ha^{-1} con el modelo exponencial a 29 kg ha^{-1} con el modelo cuadrático con plateau al considerar una relación de precios nitrógeno-trigo igual a dos y fósforo-trigo igual a cuatro. Los resultados muestran que las recomendaciones de fertilización dependen en gran medida de la elección del modelo y que debido al diseño usual de los tratamientos de fertilización que incluyen niveles de nitrógeno de 0 a 200 ó más kg ha^{-1} no se dispone de información suficiente para la discriminación entre los modelos utilizados.

Palabras clave: Triticum aestivum *L., dosis óptima económica, dosis óptima fisiológica, modelos de regresión, regresión no lineal.*

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SUMMARY

In this paper, nitrogen and phosphorus fertilizer requirements for wheat (*Triticum aestivum* L.) in the Yaqui Valley, obtained with four response models, are analyzed and the computational programs in SAS (Statistical Analysis System) for adjusting these models are provided. Nitrogen and phosphorus recommendations are based on data for three experiments conducted with farmers. Grain yield variation was described by four response models with various levels of complexity (quadratic, quadratic plus plateau, sine and exponential models). Most of these models fit the data equally well when evaluated using the R-square criterion, but there were marked discrepancies between the quadratic plus plateau model and the other models when predicting economic optimum rates of nitrogen. Economic optimum rates of nitrogen range from 106 with the quadratic plus plateau to 138 kg ha^{-1} with the sine model and economic optimum rates of P_2O_5 range from 15 with the exponential model to 29 kg ha^{-1} with the quadratic plus plateau at a two-to-one nitrogen-to-wheat and four-to-one phosphorus-to-wheat price ratios. The results show that fertilizer recommendations can be very dependent on choice of model, even when the data on which they are based do not contain the information needed to make a model choice.

Index words: Triticum aestivum *L., economically optimum fertilization, physiologically optimum fertilization, regression models, non linear regression.*

INTRODUCCION

El trigo de primavera sembrado en invierno es el cultivo más importante del sur de Sonora; en particular, en el Valle del Yaqui se siembran aproximadamente 120 000 ha, con un rendimiento promedio de 5 t ha^{-1}. Aunque existen recomendaciones de fertilización para este cultivo, las dosis, invariablemente, se han calculado utilizando el modelo cuadrático con interacciones de dos factores, suponiendo implícitamente que este modelo proporciona la mejor aproximación a la ley natural de este fenómeno. En este trabajo, cuestionando la bondad del modelo cuadrático, las recomendaciones de fertilización se calculan con diferentes modelos, para estudiar el efecto del modelo de respuesta utilizado en las recomendaciones de fertilización. Como los resultados obtenidos son sorprendentes, se proporcionan los programas de cómputo en SAS para el ajuste de los modelos utilizados, de tal forma que puedan ser reproducidos con facilidad por los investigadores interesados.

En el Valle del Yaqui se han efectuado una gran cantidad de trabajos para establecer recomendaciones de fertilización. Félix (1984) obtuvo las dosis óptimas económicas de nitrógeno y fósforo para dos rotaciones de cultivos. Rodríguez (1985) calculó las dosis óptimas económicas de fertilización utilizando experimentos con rotaciones de cultivos de 1956 a 1980. Moreno (1988) obtuvo las dosis óptimas económicas para N con un modelo de regresión utilizando a los días de descanso del predio como variable independiente; en todos estos estudios, como es usual en los experimentos con fertilizantes, se utilizó el modelo cuadrático.

Cady y Laird (1969), al estudiar el efecto de utilizar un modelo para derivar recomendaciones de fertilización cuando otro es el modelo verdadero, denominaron como sesgo al área comprendida entre las dos funciones de producción (la verdadera y la postulada) y encontraron que el factor que más contribuye al sesgo es el modelo postulado. Es conveniente aclarar que Cady y Laird (1969) suponen que el modelo verdadero es un modelo multinomial. En realidad, el modelo verdadero se desconoce y para derivar recomendaciones de fertilización sólo queda la posibilidad de aproximarlo con modelos matemáticos simples en la medida de lo posible.

La National Academy of Sciences (1961) describe varias funciones para modelar la respuesta a los fertilizantes. Estos modelos tienen las siguientes características: al principio la función se incrementa al aumentar la disponibilidad del nutrimento, posteriormente se alcanza un máximo y la función disminuye (modelo cuadrático) o bien el incremento tiende a cero y la función se torna asintótica (modelo exponencial).

La utilización del modelo cuadrático tiene una justificación muy importante: cualquier función continua puede aproximarse por medio de un polinomio y el modelo cuadrático es parte de un polinomio, sin embargo, Cerrato y Blackmer (1990), al comparar tres modelos para describir la respuesta del maíz a la aplicación de fertilizantes, encontraron que este modelo tiende a sobrestimar las dosis óptimas económicas y que, en consecuencia, es recomendable comparar varios modelos antes de emitir recomendaciones de fertilización.

Otro modelo comúnmente utilizado es el exponencial, el cual, según Rudin (1987), es la función más importante de las matemáticas. Como cualquier función continua puede ser aproximada también por medio de senos y cosenos (Rudin, 1987), se utilizará un modelo con esta función y se comparará un modelo de uso reciente (el cuadrático con plateau que según Bullock y Bullock (1994) es preferible al modelo cuadrático para predecir recomendaciones de fertilización para maíz), señalando que las pérdidas económicas por la utilización del modelo cuadrático en lugar del modelo cuadrático con plateau no siempre son significativas. No se utilizaron multinomios con coeficientes fraccionarios como los reportados por Cady y Laird (1969) porque implican la utilización de un mayor número de parámetros.

MATERIALES Y METODOS

Los investigadores del Centro de Investigaciones Agrícolas del Noroeste (CIANO) establecen anualmente varios experimentos de fertilización con los cultivos más importantes para afinar y verificar las recomendaciones de fertilización existentes. En este trabajo se analizan los resultados de tres experimentos establecidos en 1993 con agricultores cooperantes; en cada experimento se utilizó un diseño en bloques al azar con cuatro repeticiones y 16 tratamientos de fertilización (Cuadro 2) elegidos de acuerdo con un cuadrado doble con tres tratamientos adicionales, uno de los cuales contiene potasio (para determinar el efecto de este elemento, se compararán los tratamientos ocho y dieciséis que difieren sólo en este elemento). En primer término, se efectuó un análisis conjunto (Cuadro 1) con las localidades como parcelas grandes y los tratamientos de fertilización como parcelas chicas, aunque se detectaron diferencias significativas (α=0.05) entre localidades, debido a que se consideran parte del mismo agrosistema, se utilizarán los rendimientos promedios para el ajuste de los cuatro modelos de respuesta (el modelo cuadrático comúnmente utilizado, el cuadrático con plateau, el senoidal y el exponencial) utilizando los procedimientos GLM y NLIN del SAS (SAS User's Guide, 1989).

Modelos Estudiados

En los modelos que a continuación se describen no se incluyó el término correspondiente al potasio debido a que el efecto de este elemento no resultó significativo; en forma similar, la interacción nitrógeno-fósforo se estimó pero no se incluyó en los modelos por dos razones: por no resultar significativa y para simplificar la descripción de los modelos utilizados.

El modelo cuadrático común para nitrógeno y fósforo es:

$$Y = b_0 + b_1 N + b_2 N^2 + b_3 P + b_4 P^2 + E \quad (1)$$

donde Y es el rendimiento de grano del trigo (kg ha^{-1}); N y P son las dosis de nitrógeno y fósforo en kg ha^{-1}); b_0 es la ordenada al origen, b_1 y b_2 son los coeficientes lineal y cuadrático para nitrógeno, b_3 y b_4 son los coeficientes lineal y cuadrático para fósforo, y E representa al error.

El modelo cuadrático con plateau en nitrógeno, y cuadrático en fósforo se define como:

$$Y = b_0 + b_1 N + b_2 N^2 + b_3 P + b_4 P^2 + E \quad \text{si } N < N_0$$
$$Y = b_0 + b_1 N_0 + b_2 N_0^2 + b_3 P + b_4 P^2 + E \quad \text{si } N \geq N_0 \quad (2)$$

donde Y, N, P, E y b_i se definieron anteriormente, N_0 es la dosis crítica de fertilización que ocurre en la intersección de la respuesta cuadrática y la línea del plateau (Figura 1), esta dosis crítica, que usualmente es diferente de la óptima, se obtiene con dos condiciones: la curva debe ser continua y la derivada en N_0 debe ser igual a cero. No se utilizó el modelo cuadrático con plateau en nitrógeno y fósforo debido a que el plateau para fósforo se localizó en una dosis menor que 50 kg ha^{-1} y el número de tratamientos que cumplían esta condición resultaron insuficientes para estimar los parámetros que el modelo requiere.

El modelo senoidal en nitrógeno y fósforo se define como:

$$Y = b_0 + b_1 \text{Sen}(b_2 N) + b_3 \text{Sen}(b_4 P) + E \quad (3)$$

donde Y, N, P, E y b_0 se definieron anteriormente, Sen es la función seno (en radianes), b_1 y b_2 son parámetros de escala para N, y b_3 y b_4 son parámetros de escala para P. Para modelar el ascenso y descenso del rendimiento por medio de la función seno se establecieron las restricciones $0 \leq b_2 N \leq \pi$ y $0 \leq b_4 P \leq \pi$.

El modelo exponencial en nitrógeno y fósforo es:

$$Y = b_0 - b_1 \text{Exp}(- b_2 N) - b_3 \text{Exp}(- b_4 P) + E \quad (4)$$

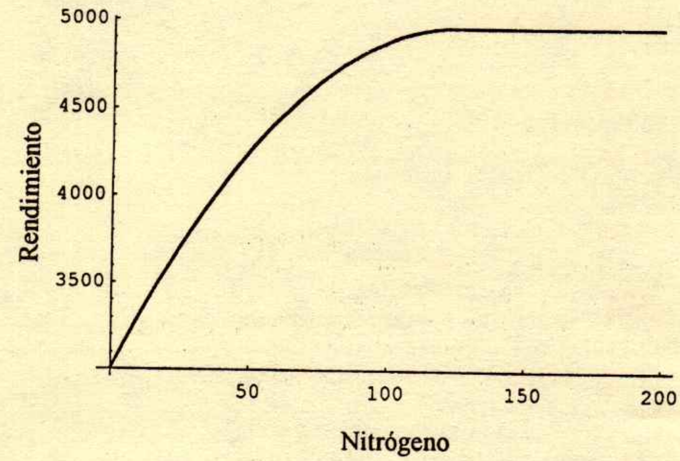

Figura 1. Modelo cuadrático con plateau.

donde Y, N, P, E y b_0 se definieron anteriormente, Exp es la función exponencial, b_1 y b_2 son parámetros de escala para N, y b_3 y b_4 son parámetros de escala para P. Note que b_0 es el máximo rendimiento predicho por el modelo y que este término es equivalente al parámetro M dado por Cerrato y Blackmer (1990). El Modelo 4 se puede considerar como una generalización del modelo de Mitscherlich para un fertilizante (National Academy of Sciences, 1961), que se define como:

$$Y= M\,[1- \text{Exp}(-c(N+b))]$$

Con la equivalencia $M = b_0$, $M\,\text{Exp}(-cb) = b_1$, y $c = b_2$ este modelo es:

$$Y = b_0 - b_1 \text{Exp}(-b_2 N).$$

Observe que los Modelos 3 y 4 son más fáciles de interpretar que el modelo cuadrático, el coeficiente b_1 es la máxima contribución del nitrógeno y el coeficiente b_3 es la máxima contribución del fósforo al rendimiento del trigo.

Los siguientes programas básicos en SAS ajustan los modelos descritos a las medias de tratamientos, para más detalles por favor consultar el procedimiento NLIN del SAS.

```
'1. En esta parte del programa se introducen los datos'
DATA A;
INPUT  T N P K Y;
N2=N*N;
P2=P*P;
NP=N*P;
CARDS;
```

```
1 0 0 0 3539.87
1 0 50 0 3649.60
.
.
16 100 50 40 5327.51

'2. Ajuste del modelo cuadrático '
PROC GLM;
MODEL Y= N N2 P P2;RUN;

'3. Ajuste del modelo cuadrático con plateau '
'PARMS define a los parámetros del modelo'
'MODEL define al modelo utilizado'
'DER. proporciona las derivadas necesarias para el ajuste'
PROC NLIN DATA=A;
PARMS A=4840 B=16 C=-.05 D=6.7 F=-0.05;
N0=-.5*B/C; DB=-.5/C; DC=.5*B/C**2;
IF N < N0 THEN DO;
MODEL Y=A + B*N + C*N2 + D*P + F*P2;
DER.A=1;
DER.B=N;
DER.C=N2;
DER.D=P;
DER.F=P2;
END;
ELSE DO;
MODEL Y=A + B*N0 + C*N0*N0 + D*P + F*P2;
DER.A=1;
DER.B=N0 + B*DB + 2*C*N0*DB;
DER.C=B*DC + N0*N0 + 2*C*N0*DC;
DER.D=P;
DER.F=P2;
END;
IF _OBS_=1 & _MODEL_=1 THEN DO;
PLATEAU=A + B*N0 + C*N0*N0 + D*P + F*P2;
PUT N0= PLATEAU= ; END;

'4. Ajuste del modelo exponencial'
PROC NLIN DATA=A;
PARMS A=5438 B=1250 C=.014 D=342 E=.20;
MODEL Y=A - B*EXP(-C*N) - D*EXP(-E*P);
DER.A=1;
DER.B=-EXP(-C*N);
DER.C=B*EXP(-C*N)*N;
DER.D=-EXP(-E*P);
DER.E=D*EXP(-E*P)*P;

'5.Ajuste del modelo senoidal'
PROC NLIN DATA=A;
PARMS A=.0093 B=1149 C=3838 D=.0309 F=416.82;
MODEL Y=C + B*SIN(A*N) + F*SIN(D*P) ;
BOUNDS 0 < A < .0157;BOUNDS 0 < D < .031416;
DER.A=B*COS(A*N)*N;
DER.B=SIN(A*N);
DER.F=SIN(D*P);
DER.D=F*COS(D*P)*P;
DER.C=1;RUN;
```

Los coeficientes de determinación (R^2) para los modelos estudiados se obtuvieron del análisis de varianza. La predicción de las dosis óptimas económicas se calcularon con el procedimiento estándar descrito por Cerrato y Blackmer (1990) que consiste en expresar la ganancia neta por medio de los modelos para determinar los valores máximos con la ayuda de la primera derivada. El máximo rendimiento económico se obtuvo sustituyendo los valores calculados por el procedimiento anterior en las ecuaciones de respuesta.

RESULTADOS Y DISCUSION

El análisis de varianza conjunto muestra que existen diferencias significativas entre tratamientos a un $\alpha = 0.05$ (Cuadro 1) y aunque también se puede observar que existen diferencias significativas entre localidades y que la interacción localidades-tratamientos es significativa, debido a que los experimentos se establecieron en suelos con la misma textura, pendiente y cultivo anterior, los modelos de respuesta se ajustaron a los promedios de los tratamientos de fertilización a través de las tres localidades (Cuadro 2). Como el tratamientos dieciséis (el único que contiene potasio en una dosis de 40 kg ha^{-1}) difiere del tratamiento ocho sólo en el contenido de potasio, estos dos tratamientos se compararon por medio de un contraste que no resultó significativo, motivo por el cual este nutrimento no se incluyó en el modelo y su dosis óptima económica se fijó en 0 kg ha^{-1}.

Como la interacción nitrógeno-fósforo en el modelo cuadrático no resultó significativa a un $\alpha = 0.05$, esta interacción también se eliminó en los modelos exponencial y senoidal.

El Cuadro 3 muestra que cuando se utilizó el criterio de la estadística R^2, los cuatro modelos parecen ajustarse igualmente bien a los datos. (los programas que se proporcionan ajustan los modelos a las medias del Cuadro 2, estas medias provienen de tres localidades y cuatro repeticiones, esto es, de 12 observaciones; por esta razón, para obtener las sumas de cuadrados del Cuadro 3 es necesario multiplicar por doce a las sumas de cuadrados proporcionadas por los programas). El Cuadro 3 proporciona la predicción de los rendimientos óptimos económicos (que son muy similares) con los cuatro modelos, suponiendo una relación de precios nitrógeno-trigo igual a dos y fósforo-trigo igual a cuatro.

Cuadro 1. Análisis de varianza conjunto.

F. V.	G. L	Sumas de cuadrados	Cuadrados medios	Fc	$F_{\alpha=0.05}$
L	2	44 397 915	22 198 957	52.19*	4.25
R(L)	9	3 827 563	425 284		
T	15	84 820 693	5 654 713	41.54*	1.74
T*L	30	21 917 022	730 567	5.37*	1.54
Error	135	18 375 642	136 116		
Total	191	173 338 836			

L: Localidades. R: Repeticiones. T: Tratamientos de fertilización. Significancia a un α=0.05.

Cuadro 2. Tratamientos de fertilización y rendimiento promedio de trigo.

Tratamiento	N	P_2O_5	K_2O	Rendimiento
	- - - - - - - - -	kg	ha^{-1}	- - - - - - -
1	0	0	0	3539.87
2	0	50	0	3649.60
3	0	100	0	3608.62
4	50	25	0	4805.25
5	50	75	0	4887.89
6	100	0	0	5003.18
7	100	25	0	5319.87
8	100	50	0	5341.40
9	100	75	0	5357.37
10	100	100	0	5396.96
11	150	25	0	5421.27
12	150	75	0	5410.16
13	200	0	0	5213.61
14	200	50	0	5417.79
15	200	100	0	5169.86
16	100	50	40	5327.51
$\bar{Y}$				4929.39

El Cuadro 4 muestra una marcada discrepancia entre el modelo cuadrático con plateau y el resto de los modelos para identificar la dosis óptima económica de fertilización nitrogenada. El modelo cuadrático con plateau indica una dosis de 106 kg ha^{-1}, que es la más pequeña; el modelo exponencial fue consistente en proporcionar dosis económicas más pequeñas que los modelos cuadrático y senoidal en desacuerdo con los resultados reportados por Cerrato y Blackmer (1990), este modelo proporcionó la dosis más pequeña para fósforo (15 kg ha^{-1}). Los modelos senoidal y el cuadrático proporcionaron dosis óptimas económicas similares para los dos nutrimentos. Estas diferencias entre recomendaciones subrayan la necesidad de disponer de métodos de selección entre modelos.

Como los valores de R^2 para los modelos estudiados son similares, pero sus dosis óptimas económicas de fertilización predichas son diferentes (Cuadro 4), se necesitan otros criterios que auxilien en la selección del modelo. El análisis de residuales no fue útil, la distribución de los errores y las gráficas son muy parecidas, la Figura 2 muestra el modelo exponencial que se obtuvo y la Figura 3 muestra el modelo senoidal. Para una discriminación adecuada entre estos modelos se necesitan más niveles de nitrógeno y fósforo cercanos a las dosis óptimas económicas, es necesario utilizar el conocimiento obtenido en experimentos anteriores para delimitar los niveles de prueba en los experimentos futuros, y eliminar la práctica usual en los experimentos de fertilización que utilizan los mismos diseños de tratamientos por muchos años con niveles de nitrógeno que varían de 0 a 200 kg ha^{-1} como en los experimentos estudiados.

El Cuadro 5 presenta las pérdidas económicas, expresadas en kg ha^{-1} de trigo, que resultan de la utilización de un modelo diferente al modelo verdadero para el cálculo de las dosis óptimas económicas. Por ejemplo: si la respuesta verdadera fuera el modelo cuadrático pero la fertilización se basara en el modelo cuadrático con plateau, se aplicarían 106 kg de nitrógeno en lugar de la dosis óptima que corresponde al modelo cuadrático que es de 136 kg (se aplicarían 30 kg menos de nitrógeno que equivalen a una ganancia de 60 kg de trigo), se aplicaría 1 kg más de fósforo (que equivale a una pérdida de 4 kg de trigo) y se obtendrían 132 kg menos de trigo, así la pérdida económica expresada en rendimiento de grano sería de 72 kg ha^{-1} (132-60+4). Observe que no se cuantifican las ventajas ambientales que implica la aplicación de una cantidad menor de fertilizante.

CONCLUSIONES

Los resultados de este estudio indican que la selección del modelo de respuesta en experimentos de fertilización merece más atención de la que se les presta, especialmente cuando los modelos se utilizan para la predicción de dosis óptimas económicas. En el caso estudiado, debido a la falta de más niveles cercanos a las dosis óptimas, se carece de la información necesaria para distinguir entre

Cuadro 3. Sumas de cuadrados de los modelos utilizados.

F.V	G.L	Cuadrático	Cuadrático con plateau	Exponencial	Senoidal
Regresión	4	83 311 296	83 916 166	83 417 310	82 415 635
F. A.	11	1 509 397	904 527	1 403 383	2 405 058
Tratamientos	15	84 820 693	84 820 693	84 820 693	84 820 693
R^2		0.9822	0.9893	0.9834	0.9716
Y_{op}		5484	5335	5306	5537

F.A : Falta de ajuste. Y_{op} : Rendimiento óptimo económico en kg ha^{-1}.

Cuadro 4. Rendimientos y dosis óptimos económicos con los modelos de respuesta.

Modelo	N-P_2O_5	Modelo de respuesta
Cuadrático	136 - 28	$Y= 3525 + 24.43N-.082N^2+7.41P-.061P^2$
Cuadrático con plateau	106 - 29	$Y= 3484 + 29.66N-.130N^2+7.92P-.066P^2$ si $N\leq 113$ $Y=5168 + 7.92P - .066P^2$ si $N>113$
Exponencial	122 - 15	$Y=5417-1759Exp(-.0255N)-196Exp(-.1208P)$
Senoidal	138 - 32	$Y=3555+1823Sen(.0106N)+227Sen(.0259P)$

Cuadro 5. Pérdida económica (expresada en kg ha^{-1} de trigo) y fertilización aplicada en exceso debida a la incorrecta selección del modelo.

Modelo utilizado	Modelo verdadero			
	Cuadrático	Cuadrático con plateau	Exponencial	Senoidal
Cuadrático	0 (0,0)	60 † (30, -1)	30 (14, 13)	1 (-2, -4)
Cuadrático con plateau	72 (-30, 1)	0 (0,0)	36 (-16, 14)	104 (-32, -3)
Exponencial	27 (-14, -13)	42 (14, -14)	0 (0,0)	40 (-16, -17)
Senoidal	3 (-2, 4)	65 (32, 3)	45 (16, 17)	0 (0,0)

† Si se utiliza el modelo cuadrático cuando el modelo verdadero es el cuadrático con plateau, se obtendrán sólo 4 kg ha^{-1} menos de trigo, pero al aplicar 30 kg ha^{-1} más de nitrógeno y 1 kg ha^{-1} menos de fósforo, se tendrá una pérdida económica equivalente a 60 kg ha^{-1} de trigo.

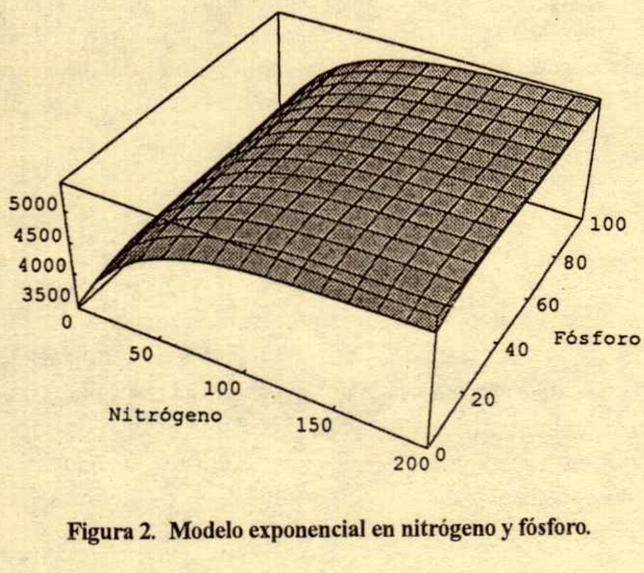

Figura 2. Modelo exponencial en nitrógeno y fósforo.

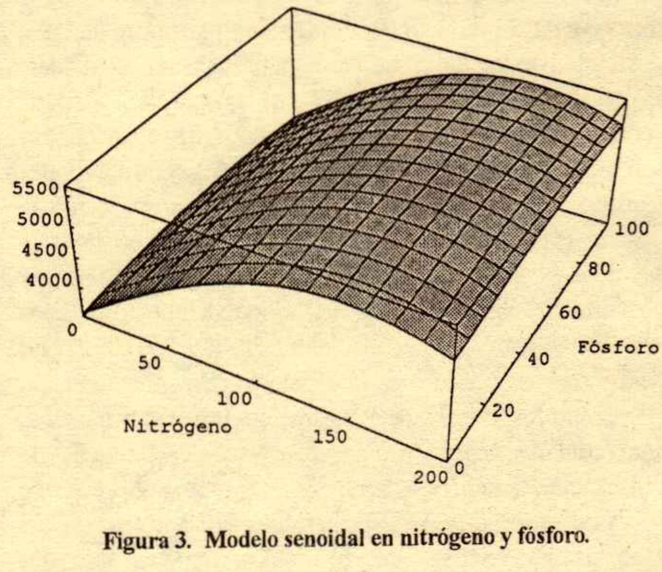

Figura 3. Modelo senoidal en nitrógeno y fósforo.

los modelos cuadrático, cuadrático con plateau, senoidal y exponencial, sin embargo, resulta claro que la elección del modelo afecta la estimación de las dosis óptimas económicas. El modelo cuadrático sobrestima las dosis óptimas económicas con relación a los modelos cuadrático con plateau y exponencial y las recomendaciones obtenidas con el modelo senoidal coinciden con las del modelo cuadrático. Los modelos exponencial y senoidal tienen una ventaja con respecto al cuadrático y cuadrático con plateau, sus coeficientes permiten identificar en forma inmediata la contribución máxima de los fertilizantes (b_1 es la contribución máxima del nitrógeno, en kg ha^{-1} de grano, y b_3 es la del fósforo). Como en condiciones de campo el suelo amortigua el posible daño causado por un exceso de fertilización, se espera que el decremento del rendimiento debido a una sobrefertilización no sea tan rápido como lo predice el modelo cuadrático y el senoidal, por esta razón, el modelo cuadrático con plateau (Figura 1) surge como una mejor opción. Para una discriminación precisa entre los modelos considerados se requiere de experimentos con más niveles de fertilizantes cercanos a las dosis óptimas económicas, esto es, se necesita un diseño de tratamientos que utilice la información de experimentos anteriores.

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SIMPOSIO
PRODUCTIVIDAD DEL SUELO Y CICLAJE DE NUTRIMENTOS EN RELACION CON UNA AGRICULTURA SUSTENTABLE DE BAJOS INSUMOS

J.Z. Castellanos, H. Hirata y A. Aguilar Santelises (editores)

INTRODUCCION

El mundo con una población creciente requiere continuamente una mayor producción de alimentos. Una de las estrategias más recurridas para lograr esta producción ha sido el uso intensivo de fertilizantes y pesticidas; como resultado, sin embargo, se tiene una mayor circulación de estos compuestos en el medio ambiente, principalmente en las fuentes de agua superficiales y subterráneas, poniendo en riesgo la sustentabilidad del ecosistema.

Uno de los fertilizantes que más daños ha causado al ecosistema es el nitrógeno, siendo los mantos acuíferos el componente más afectado. Este ha sido un problema creciente en los países desarrollados y empieza a ser un problema en los países en vías de desarrollo. No obstante estos prejuicios, el uso de este elemento es primordial para poder hacer frente a la demanda mundial de alimentos. Por ello existe un compromiso entre la utilización de los fertilizantes nitrogenados y el cuidado del medio ambiente. Una de las estrategias para utilizarlo en forma más segura es combinarlo con el uso de fuentes alternativas de N, tales como la fijación biológica de N (FBN), que podríamos explotar aún más para satisfacer parcialmente la demanda de este nutrimento y reducir así las presiones adversas sobre el ecosistema.

Las contribuciones contenidas en este volumen de Terra fueron presentadas en un simposio, realizado en el seno del XV Congreso Mundial de Suelos, el cual se organizó con el fin de hacer un análisis de la problemática que oscila alrededor de la productividad del suelo y el ciclaje de nutrimentos con relación a una agricultura sustentable y de bajo uso de insumos. Este tema tiene especial significancia para México, un país que importa fertilizantes fosforados y potásicos y que utiliza grandes cantidades de energéticos para producir fertilizantes nitrogenados.

En este simposio se analizan los balances globales de N al nivel de una nación como Japón y sus efectos sobre la circulación de este elemento en el ecosistema, así como también la posibilidad de integrar los sistemas de cultivo para reducir las entradas de este nutrimento al suelo hasta un punto que no se afecte el rendimiento ni se ocasionen pérdidas de N hacia el medio ambiente. Otro tema aquí tratado es el papel que juegan las leguminosas de grano en el aporte de nitrógeno a los sistemas agrícolas, no sólo por el N fijado directamente para su utilización inmediata, sino por los efectos residuales en el cultivo subsecuente; la rotación de cultivos es una de las alternativas más viables para manejar una agricultura de bajos insumos sin enfrentar los sacrificios en el rendimiento que se obtienen al reducir las dosis de N al cultivo.

Colateralmente, se analiza la conveniencia de los sistemas de labranza reducida, como estrategia para aprovechar más eficientemente los nutrimentos contenidos en los residuos de cultivos. Este tema se analiza sobre la base de los diferentes tipos de suelo. También se analiza el tema de la desnitrificación en los sistemas de labranza reducida, pues tradicionalmente se pensaba que al no quemar los residuos de cultivo mediante la estrategia de labranza cero se podrían reducir las fertilizaciones, sin embargo, existe evidencia de que en los sistemas de labranza reducida las pérdidas de nitrógeno se incrementan por la vía de la desnitrificación.

Por otro lado, se analiza la emisión de gases de invernadero y su relación con los diferentes sistemas agrícolas, y se realiza un balance global de carbono en donde la agricultura juega un papel importante. Además se trata la restauración de suelos degradados mediante el establecimiento de praderas y de leguminosas de grano para mejorar su fertilidad y recuperar sus niveles originales de carbono orgánico.

Finalmente se proponen indicadores económicos de la sustentabilidad, un tema emergente del que no existe mucha información, para predecir a largo plazo las repercusiones de un sistema de manejo del suelo.

SYMPOSIUM
SOIL PRODUCTIVITY AND NUTRIENT CYCLING IN RELATION TO A LOW INPUT SUSTAINABLE AGRICULTURE

J.Z. Castellanos, H. Hirata y A. Aguilar Santelises (editors)

INTRODUCTION

A world with a growing population requires increasing amounts of food. One of the strategies to attain this goal is the intensive use of fertilizers and pesticides. The result, however, has been a higher circulation of these compounds in the environment, mainly in the groundwater and surface water reservoirs, endangering the sustainability of the ecosystem.

One of the fertilizers that has caused more damage to the environment when it has been overused is nitrogen, being the aquifers the component of the ecosystem that has received the most serious damage. This is an increasing problem in developed countries and it begins to be an important problem in developing countries. Nevertheless, the use of these agrochemicals is absolutely necessary to face the high demand of food in a growing world. Therefore, there is a compromise between its utilization and the preservation of the environment. One of the strategies to utilize N fertilizer is to combine its use with alternative sources of N such as the biological nitrogen fixation (BNF), which could be partially exploited to reduce the adverse effects of the fertilizer.

The papers included in this number of Terra are the contributions of a symposium presented in the XV World Congress of Soil Science, organized with the objective of analyzing the situation of nutrient cycling in relation to soil productivity and to discuss the available technologies to meet the demands of nutrients for a sustainable agriculture, at the same time that we limit the release of these elements to the environment. This topic has special significance to Mexico, a country that imports a large amount of P and K fertilizers and that spends a large amount of fossil fuels to produce N fertilizers.

In this document N balances are presented at country level (Japan) including their effects on the circulation of this element in the ecosystem, as well as the possibility to integrate the farming systems to reduce its inputs to the soil system up to a point that crop yields are not reduced and damages to the ecosystem are not caused. Another topic that is discussed in the symposium is the role of leguminous crops to supply N to the agricultural systems, not only by the N fixed but also by the residual effects of the crop residue N on the following crop, being crop rotation one of the alternatives more feasible to manage a low input sustainable agriculture without sacrificing crop yields that usually are obtained when the rate of N is reduced below its economical optimum level. It is also discussed the convenience of using the reduced tillage strategies as a means to make a more efficient use of the nutrients in different soil types. However, it is recognized the importance of the denitrification that occurs in the conservation tillage systems.

The impact of agriculture in the carbon balance and on the emission of greenhouse gases is discussed as well. In another topic, ways to restore degraded soil by using pasture and grain legume crops are analyzed. Finally some economic indicators are discussed to measure or estimate sustainability in agricultural systems, a topic for which there is not much information yet.

NUTRIENT CYCLING CONSIDERATIONS FOR SUSTAINABLE AGRICULTURE

Consideraciones sobre el Ciclaje de Nutrimentos en la Agricultura Sostenible

T. Hakamata[1] and H. Hirata[2]

SUMMARY

Nutrient cycling at national and international levels is discussed. Nitrogen cycling in Japan is given as an example of an area where large amounts of N are imported and accumulated causing water and soil pollution.

Index words: *Nitrogen cycling, Japan.*

RESUMEN

El ciclaje de nutrimentos se discute a escalas nacionales e internacionales. El ciclaje de N en Japón se discute como ejemplo de un área en donde grandes cantidades de N son importadas y acumuladas, causando la contaminación del agua y del suelo.

Palabras clave: *Ciclaje de N, Japón.*

Victor Hugo (1862) said "Each belch of our cloaca costs us a thousand francs, and the result is that the land is impoverished and water made foul". It can be said from the nutrient cycling point of view that the same situation has been continued even until today, although the facilities of sewerage systems have been improved to gain clearer water from polluted water in even the most developed urban area. Imbalance in nutrient cycling is common almost all over the world and seems to cause the most water pollution and famine, that is, the input into society from our environment is about 70 million ton larger than the output. The amount is derived from the industrial nitrogen fixation and is finally returned again to the environment including terrestrial aquatic area and oceans. Sustainability of ecosystems is of critical importance especially in food and feed systems. We have to focus on some points along the process of nutrients from the industrial intake to the output into environments, especially on food and feed trade, nutrient cycling in a country and/or a local area, each crop system and such a depositing system as a sewerage system. We have to remember the law of nutrient cycling in ecosystems to realize the soil utilization in harmony with nature and the sustainable system.

Nutrient Cycling on International Scales

There are differences between countries in nutrient cycling, consequently in the budget. The budgets in some countries show higher input of nutrients to their national lands than the output of them; in other countries, higher output and lower input. Miwa (1990) showed the flow of nitrogen through the international food and feed trade. Nitrogen from the U.S.A., Canada, Argentina, Australia, France, Thailand, Denmark, and Peru flowed into Japan, U.S.S.R., F.R. of Germany, Spain, U.K., China, the Netherlands, Poland, Mexico, Egypt, Korea, Belux, and other countries. While the export flow is overwhelmed by the U.S.A. and executed by a small number of countries, and import of nitrogen is scattered through many countries in the world, nitrogen imported/exported per area of arable and permanent grassland of each country shows another figure (Figure 1). The largest exporter is not the U.S.A but Norway, which exports about 50 kg ha^{-1}. Denmark, Suriname, France, and Thailand rank above the U.S.A. and Canada. Large importers are Japan, the Netherlands, Belux, Korea, Egypt, Israel, Germany, and Switzerland.

Generally speaking, the developing countries remove small amounts of nutrients from agricultural lands and return smaller amounts. Sub-Saharan Africa, however, is the only region in the world where the per

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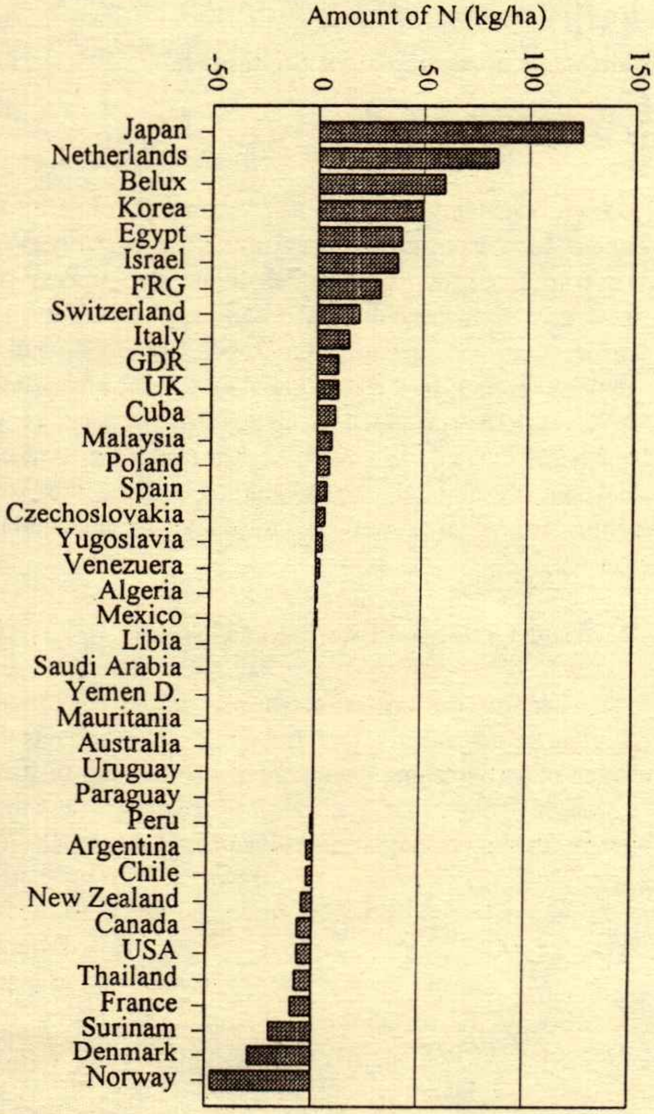

Figure 1. Nitrogen imported per area of arable and permanent grassland. (Miwa, 1990)

capita food production has decreased during the past 25 years (Smaling, 1991). We can see imbalance of nutrient budgets (Hakamata, 1992) and depletion of soil fertility (Smaling, 1992; Pieri, 1989) in some area/countries in Africa. We have to think about not only low input strategy but also high input one in some areas or countries for realizing sustainable systems in a food and feed system in the world.

Nutrient Cycling on National Scale... Experiences in Japan

We believe that the way toward the sustainable agriculture can take into account the serious experiences of high input nutrients in Japan. The land of Japan has been enormously loaded with nutrients because of the import of large amounts of food and feed (Hakamata, 1990; Figure 2). Imported food and feed are stocked, processed, traded and utilized. A large part of them are wasted as animal, home and industry waste. Nitrogen waste from the system are carried into the environment including agricultural lands. Besides this, chemical fertilizers and byproducts of crops were loaded into the environment, making a total of about 2,400 kt of nitrogen in 1987. This causes the problems of water and livestock pollution.

In 1960, the Doubling Program of National Income was submitted to the Japanese cabinet meeting, and nitrogen flowed more through domestic production than import (Miwa & Iwamoto, 1988). 609 kt of nitrogen were wasted to the environment. This is about 40 % of the 1987 levels. Dietary habits in Japan have been changed during these decades. An intake of grain has decreased by 30 %, that of protein has increased by 26 % and that of fat has increased to near three times of 1960's level. The number of livestock animals has increased during the days. Nutrients derived from animal waste show remarkable increase after that. At the same time, livestock farmers have dramatically decreased. Most of them do not feed the animals on roughage from their own farmlands but mainly on concentrates, more than 90 % of which is imported from foreign countries. This means the animal wastes are concentrated in so limited places that they tend to be not effectively returned to agricultural lands. Only 50 % if pig excreta has been returned to agricultural lands after 1970s. By the way, only less than 10 % of sewage sludge is used as fertilizers in Japan because of mainly high level of such toxic chemicals as heavy metals, etc.

639 kt of chemical fertilizer nitrogen was used in 1960 which is not so different from the 1987 figure .

Can we manage such a large amount of nitrogen in agricultural lands in Japan as mentioned above? We had 5.53 million ha of cropping land in 1987. If we returned whole nitrogen to the land, fertilizing rate of nitrogen would be 430 kg ha^{-1} (including nitrogen from chemical fertilizers and byproducts of crop). This level is higher than the nitrogen carrying capacity of agricultural lands in Japan, which is estimated to be 250 kg ha^{-1} by Nishio (1993), and than the upper standards of nitrogen fertilization (100 kg for paddy

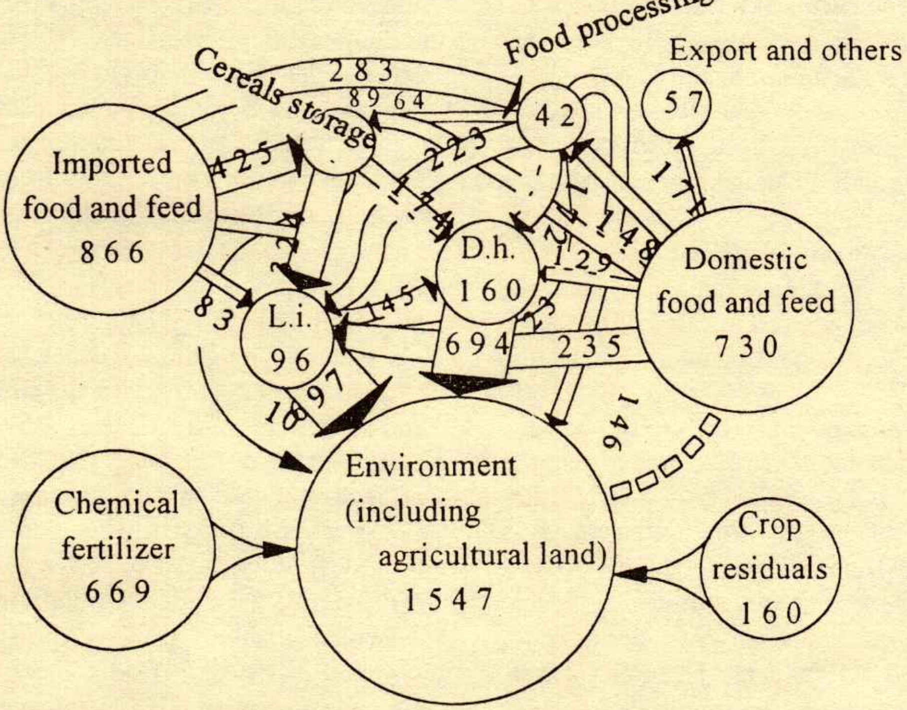

Figure 2. Nitrogen cycling through the food and feed system in Japan in 1987 (thousand t; Hakamata, 1990). L.i. Livestock industry. D.h. Dietary habits.

rice or ordinal upland crops, 200 kg ha^{-1} for vegetables and 230 kg ha^{-1} for herbage).

Can we secure enough area to produce the same amount of feed as imported in Japan? The necessary area of crop lands can be estimated to be 5.79 million ha (4.10, 1.23 and 0.46 million ha for corn, for sorghum and for barley, respectively) supposing average yield of each crop equals 3 t ha^{-1}. Area of agricultural land and planted field and cropping ratio, which have been decreasing, should increase and techniques for such high yield as 4.7 t ha^{-1} for corn and 10 t ha^{-1} which are established in Japan should be extended to realize it. Agro-Forestry is also useful even in Japan (Okubo, 1987).

Future prospects for integrated farming systems in Japan are reported by Kon-no *et al.* (1994) in our symposium IV-A.

Nutrient Cycling on a Local Scale

The situation is similar on a local scale in Japan. For example, in the Ushiku Lake basin in a central part of Japan, which has a total area of about 160 km^2, about one-third of which is cultivated, and has only a small weight of livestock farming, a total of a little over 50 thousand tons of organic materials including nutrients are discharged every year to agricultural land or the environment (Matsumoto *et al.*, 1992a, 1992b). The sources of these materials are derived from our dietary habits, livestock farming and by-products of agriculture. If all of the organic matter could have been recycled to the agricultural land, the amount of mineralized nitrogen in the soil would have reached 138 kg ha^{-1}. The amount exceeds nitrogen in chemical fertilizers used in the area. Increase of nitrate nitrogen level of ground water was recently reported in the area.

Reasonable and maximun rates of organic nitrogen application were estimated on the basis of the nitrogen budget in the area. The reasonable rates under the actual nitrogen application (70-120 kg ha^{-1}) were 30-70 kg ha^{-1}. The maximun rates which assumed complete replacement of inorganic nitrogen by organic sources were 140-160 kg ha^{-1}. The amount of organic nitrogen generated in the area exceeded the reasonable rate but was within the maximum rate. This fact shows that the organic nitrogen generated in the area can be used as an alternative to chemical fertilizer nitrogen.

Nutrient Cycling on a Farmland Scale

We can see examples of relatively closed system of nutrient cycling in a paddy field and a grazing pasture in Japan. Nitrogen purifying function of paddy fields is reported by Ogawa & Sakai (1984) and Kon-no *et al.* (1994). We will now give an example of nitrogen cycling in a heifer pasture studied in eastern Hokkaido, a northern island of Japan (Hakamata & Hirashima, 1978).

A major part of nitrogen absorbed by the herbage from the soil is grazed by heifers. A part of them is used by their bodies, and a residual part is returned to the soil in the form of excreta. Ungrazed herbage is divided into edible and inedible parts. The majority of them will eventually decompose into the soil. Only such nitrogen as is consisted of the increment of heifer bodies must be taken off from the pasture. Gaseous nitrogen is also reported to be released from the surface of a pasture into the atmosphere. 14 % of the nitrogen is eventually taken out from the system, with 86 % returning to the soil. Generally speaking, 80-90 % of nitrogen is returned to the soil in a grazing pasture system. We can understand that nutrient cycling system in a pasture is not only relatively closed but also structurally complex and well-controlled by a lot of natural processes (Hakamata, 1986, 1990).

We have to learn from such a system as a nutrient cycle keeps the balance in harmony with nature.

CONCLUSION

Justus Von Liebig (1876) said "The fundamental principle of... Japanese agriculture is to replenish all nutrients removed from the soil by the harvesting of crops". From 12th century, when our ancestors began to apply human excreta to agricultural lands in Japan, human excreta had been completely returned to increase soil productivity until the early stage of 20th century. Most waste produced from our lives had been returned even in 1950s. Nutrient cycling through food and feed systems was also limited in environmental loading in 1960. In the 1960s the economy of Japan went into a period of high growth and introduced technological innovation even in agricultural fields. The process after that was undertaken without proper attention to the environment and the result was serious pollution-related damage. It was only after experiencing this damage that Japan began implementing proper pollution control measures. An approach to economic development which includes pollution control is much more fruitful than one which neglects environmental issues even from a purely financial standpoint (Study Group for Global Environment and Economics, 1991). We have to learn from the past to face the future.

We have to realize the new balanced system of nutrient cycling by learning from the traditional agricultural systems in Japan. The general necessary conditions are as following: (1) The self-sufficient ratio of food and feed should increase in a country. (2) Construction (reconstruction in some developed countries) of toxicant free sewerage systems should be realized. (3) New organic fertilizers and fertilizing technologies should be developed following the new sewerage systems. (4) All other techniques in each cropping system should be innovated in harmony with nature from nutrient cycling point of view.

Each paper in the volume propose how to realize the sustainable agriculture not only in each country or area but also in the world from nutrient cycling point of view.

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FUTURE PROSPECT FOR INTEGRATED FARMING SYSTEM IN JAPAN IN RELATION TO MINERAL CYCLING AND SUSTAINABLE AGROECOSYSTEM TO ESTABLISH THE ENVIRONMENTAL-PRESERVATION-TYPE SYSTEM

Futuros Prospectos para Sistemas de Granja Integrados, en Japón, con Relación al Ciclaje Mineral y al Agroecosistema Sostenible para Establecer un Sistema para la Preservación del Medio Ambiente

T. Konno[1], M. Uwasawa, and Y. Ozaki

SUMMARY

To minimize nitric stress on the environment from agricultural production, the amount of nitrogen application per unit area will be restricted within the Nitrogen Environmental Assimilating Capacity (NEAC) of every cultivated land. We will define (NEAC) as a yearly average amount of nitrogen that can satisfy not only productivity requirements, but also environment preservation requirements. We propose the bases to estimate NEAC, and estimate the value of NEAC in volcanic ash soils under vegetable cropping by using lysimeter test data. Paddy soils have higher purifying capacity for nitrate nitrogen (NO_3-N) than ammonium nitrogen (NH_4-N). If NH_4-N concentration in irrigation water does not exceed 6 mg L^{-1}, total nitrogen (T-N) concentration in permeated water can be kept lower than 1 mg L^{-1} throughout the year. But if NH_4-N concentration exceeds 10 mg L^{-1}, T-N concentration in permeated water increases during winter season. In order to satisfy the environmental quality standard for lakes and reservoirs (Type V in Japan), annual load should be less than 330 kg N ha^{-1}. Paddy fields and forest areas have also NO_3-N purifying functions on spring groundwater from upland field. We can use these functions to preserve quality of groundwater and water in closed water areas. More studies must be conducted to investigate the NO_3-N purifying capacity of paddy fields and forest areas to establish environmental preservation-type land utilization. We have to expand beneficial utilization of organic waste compost for green and agricultural land through the competition with chemical fertilizers. High quality should be attached to organic waste compost, such as efficiency to keep or increase soil fertility and activity of soil micro-organisms and also to be able to handle with ease. The establishment of permissible level of Zn of soil (120 mg kg^{-1}) restricts use of sewage sludge compost on agricultural land in Japan. Monitoring with the method of soil micro-organisms activity may be useful to review the strict management standard of Zn concentration in soil. When we applied $ZnSO_4$ and sewage sludge to some kinds of soil up to 120 mg Zn kg^{-1} or higher level, soil micro-organisms growth rate was not inhibited in certain kinds of soil. The permissible level should be established to each kind of soil.

Index words: Sewage sludge, paddy fields, forest areas, nitrogen cycle.

RESUMEN

Para minimizar el estrés nítrico sobre el medio ambiente por la producción agrícola, se restringirá la cantidad de nitrógeno aplicado por unidad de área dentro de la Capacidad Asimilable de Nitrógeno Ambiental (NEAC) de cada tierra cultivada. La NEAC se define como una cantidad media de nitrógeno anual que puede satisfacer no solamente los requerimientos de productividad, sino también los requerimientos para preservar el medio ambiente. Se proponen las bases para estimar la NEAC y estimar el valor de NEAC en suelos de cenizas volcánicas bajo cultivo, usando datos de pruebas con lisímetro.

Los suelos de arrozales tienen una capacidad de purificación más alta para nitrógeno nítrico (NO_3-N) que para nitrógeno amoniacal (NH_4-N). Si la concentración de NH_4-N en aguas de riego no rebasa 6 mg L^{-1}, puede ser que la concentración del nitrógeno total (T-N) en agua filtrada sea inferior a 1 mg L^{-1} durante todo el año. Pero, si la concentración de

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NH_4-N sobrepasa 10 mg L^{-1}, la concentración T-N en agua filtrada aumenta durante la época invernal. Para satisfacer el estándar de calidad ambiental para lagos y presas (Tipo V en Japón), la cantidad anual tendría que ser menor que 330 kg N ha^{-1}. Los arrozales y las áreas forestales también tienen funciones de purificación del NO_3-N de aguas de manantial de zonas altas. Estas funciones se pueden usar para preservar la calidad del agua freática y el agua en presas. Se tienen que conducir más estudios para investigar la capacidad de purificación del NO_3-N en campos arrozales y áreas forestales para establecer un uso de la tierra de tipo preservación ambiental.

Tiene que aumentarse la utilización benéfica de la composta orgánica residual para tierras verdes y agrícolas a través de la competencia con fertilizantes químicos. Tiene que darse mayor calidad a la composta orgánica residual, tanto en su eficiencia para conservar o incrementar la fertilidad del suelo y la actividad de los microorganismos, como en el poder manejarla fácilmente.

La implantación de un nivel permisible de Zn en el suelo (120 mg kg^{-1}) restringe el uso de la composta de residuos en suelos agrícolas en Japón. El monitoreo con el método de la actividad de los microorganismos del suelo puede ser útil para reexaminar el estándar del manejo estricto de la concentración de Zn en el suelo. Cuando se aplicó $ZnSO_4$ y desechos a algunos tipos de suelo en cantidades de 120 mg Zn kg^{-1} o más, no se inhibió el crecimiento de los microorganismos en ciertos tipos de suelo. El nivel permisible debe establecerse para cada tipo de suelo.

Palabras clave: *Sedimento residual, arrozales, áreas forestales, ciclo de nitrógeno.*

INTRODUCTION

Groundwater is one of the important resources in Japan. It is the primary source of drinking water specially in rural areas. However, groundwater contamination has become one of the serious environmental problems. NO_3-N is the most widespread contaminant of groundwater. Industrial and human waste disposal, intensive cropping and heavy fertilizer application contribute to the accumulation of NO_3-N in the groundwater system.

The Ministry of Agriculture, Forestry and Fisheries of Japan decided in 1992 to promote environmental preservation-type agriculture which means an agriculture friendly for the environment utilizing resources of organic waste. To promote agriculture like this, it is important to grasp nitrogen cycle and to estimate Nitrogen Environmental Assimilating Capacity (NEAC) that can satisfy not only productivity requirements, but also environment preservation requirements.

There is a huge output of organic waste as compared with the arable land area in Japan. Organic waste usually has high concentration of heavy metals. To recycle nitrogen of organic waste, it is important to preserve the recycling function of agricultural land from the toxicity of heavy metals.

In this paper we propose the bases to estimate the value of NEAC and a land utilization plan to preserve the rural environment. And we also introduce how we use organic waste, especially sewage sludge, avoiding the material recycling function in arable land.

Nitrogen Cycle of Agriculture Ecosystem and Nitrogen Application in Japan

Nitrogen in imported feed and food to Japan is increasing nitric stress on the environment from the agricultural ecosystem.

As shown in Figure 1, nitrogen cycle is not working effectively in Japan. The flow from livestock waste to the environment is increasing. Iwamoto and Miwa (1985) estimated that nitrogen discharge as livestock waste was 724 000 ton, of which the beneficial use as animal manure was 300 000 N ton, and the other 424 000 N ton might be nitric stress on the environment (Iwamoto and Miwa, 1985). Besides flows shown in Figure 1, there are flows from food and agricultural products to cultivated land and the environment. Sewage sludge carries these flows. The amount of sewage sludge produced in Japan was 2 590 000 m^3 in 1990, and will be 3 310 000 m^3, 90 000 ton nitrogen, in 1995 (Horie and Yokota, 1993). As mentioned above, Japan now faces a new situation. Consumption of chemical fertilizer nitrogen is on a lowering trend and is below the 700 000 ton level, on the other hand nitrogen discharge as livestock waste now exceeds the 700 000 ton level in a year. As shown in Table 1, the amount of nitrogen in sewage sludge is not so big compared to the amounts of chemical fertilizer and livestock waste nitrogen. But the amount of sewage sludge is increasing. The

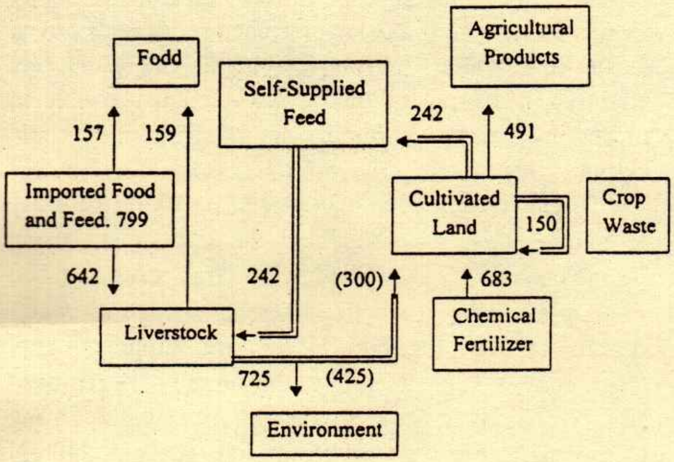

Figure 1. Nitrogen cycle (═══) in Japan.
Unit: Thousand tons ( ) is an estimated value.

Table 1. Amount of nitrogen in various forms and the average amount applied to cultivated land.

Nitrogen form	Amount of N	N	Ratio
	Thousand tons	kg ha^{-1}	%
Chemical fertilizer	683	142	41
Crop residue	150	31	9
Livestock waste	724	151	44
Sewage sludge	90†	19	6
Sum	1647	343	100

† Estimation in 1995.

value of total nitrogen per cultivated land area is estimated 343 kg ha^{-1}.

As shown in Table 2, averages of applied nitrogen are less than 150 kg ha^{-1} for rice, wheat, potatoes, cereals, and beans. Influences on the environment may be relatively small in cases of these crops. However, averages of applied nitrogen are over 200 kg ha^{-1} for each vegetable, tea, and mulberry cultivation. Vegetable farmers apply much more nitrogen because of the continuous vegetable cropping system. Due to the heavy fertilization, the concentrations of nitrate nitrogen in the underground water of vegetable fields are higher than those of paddy fields (Figure 2) (Hidaka and Yamaguchi, 1992).

Nitrogen Environmental Assimilating Capacity (NEAC) of Cultivated Land

To minimize nitric stress on the environment from agriculture production, it is necessary to estimate the value of Nitrogen Environmental Assimilating

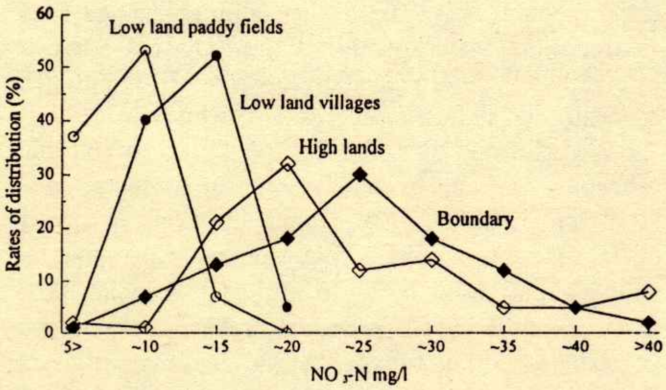

Figure 2. Nitrate nitrogen concentration in underground water of plateau utilized as livestock. Village and vegetable fields compared with those of low land fields.

Table 2-1. Amount of nitrogen applied to common crops.

Crop	Range	Average	Cropped area
	- - - N kg ha^{-1}	- - -	Thousand ha
Rice	40-140	89	2235
Wheat	40-165	93	384
Sweet potato	20-150	52	66
Potato	55-210	119	128
Cereals	10-150	49	29
Beans	10-130	36	272

Table 2-2. Amount of nitrogen applied to the other crops.

Crop	Range	Average	Cropped area
	- - - - N kg ha^{-1}	- - - -	Thousand ha
Vegetables			
open field	110- 600	213	627
protected	75- 510	266	42
Fruit trees	65- 320	171	399
Industrial crop	40- 600	214	142
Tea	120-1000	580	62
Mulberry	60- 400	270	114
Tobacco	71- 320	126	57
Forage	20- 400	109	331
Pasture	30- 400	82	718

Capacity (NEAC) on every soil type and every climatic province. We will define NEAC here as a yearly average amount of nitrogen that can satisfy not only productivity requirements (from the aspect of the topography and cropping system), but also environment preservation requirements.

We would like to propose the bases to estimate NEAC by using lysimeter test data as follows.

1) Nitrogen recovery rate by crops to total input of nitrogen should be higher than 50%. This rate should not decrease year by year.

2) Average of nitrogen concentration in permeated water should not exceed the permissible level of environmental water quality (10 mg NO_3-N L^{-1}) settled by National Environmental Agency. This nitrogen concentration should not increase year by year.

We estimated that the value of NEAC in volcanic ash soils was approximately 250 (in northern part) ~350 (in southern part of Japan) kg N ha^{-1} in a year under vegetable cropping. We estimated this value by applying the above bases to nitrogen balancing data from forage crops-, common upland crops- and vegetables-cultivation experiments. These experiments were carried out by the method of lysimeter (the least area 10 m^2, depth 1) in Iwate, Yamanashi and Ohita prefectures in 1974-1981 (Figure 3, Table 3, Table 4). Amount of total nitrogen per cultivated land area (as shown in Table 1, the value is 343 kg N ha^{-1}) is more than the value of NEAC in volcanic ash soils (Uwasawa, 1993).

From now on, the amount of nitrogen applied in a year or in one cycle of cropping system may be restricted within the value of NEAC. It is obvious that beneficial use of organic waste nitrogen on cultivated land has to expand through the competition with chemical fertilizer nitrogen.

Nitrogen-purifying Capacity of Paddy Field

Table 5 shows the capacity of the paddy fields or soils in purifying nitrogen. The daily amounts of nitrogen removed per hectare increase as the nitrogen concentration in irrigation water increases. Paddy fields can remove 0.2-2 kg per hectare per day even during the winter season (Tabuchi, 1991). Hence, effective utilization of this ability is indispensable in preserving the water quality in a terrain-crop chain system.

To clarify the value of nitrogen purifying capacity of paddy soils, we conducted the experiment using lysimeters (0.216 m^2) filled with Gray Lowland soil from plow layer. About 30 mm irrigation water containing 0-20 mg NH_4-N L^{-1} was supplied every other day. Table 6 shows the amount of removed NH_4-N. The average T-N concentration was 0.58 mg L^{-1} in permeated water from soil without NH_4-N application. With average N concentration in weigh per volume of rain and irrigation water at 0.95 mg L^{-1}, the soil can remove about 26 kg NH_4-N per hectare in a year. When irrigation water with 10 mg NH_4-N L^{-1} was supplied, average T-N concentration in permeated water became 1.9 mg L^{-1}, removing 394 kg NH_4-N ha^{-1} d^{-1}. The result shows that we have to control NH_4-N concentration in irrigation water (15 mm per day) lower than 6 mg L^{-1} to restrain T-N concentration in permeated water lower than 1 mg L^{-1} and annual load should be less than 330 kg NH_4-N ha^{-1}.

Paddy soil also has the function purifying NO_3-N. Figure 4 shows the changes of T-N concentration in permeated water from paddy field in lysimeter (0.5 m^2) during fallow period. We applied rice straw on the soil surface to augment nitrogen purifying capacity and supplemented irrigation water containing 25 mg

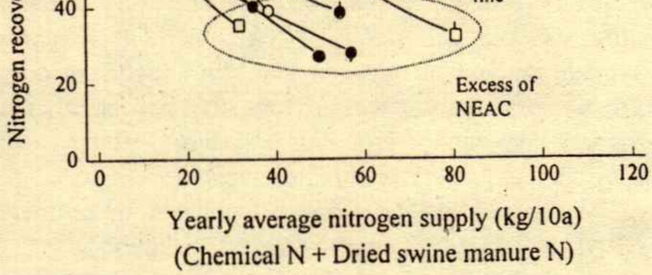

Figure 3. Yearly average nitrogen supply and average nitrogen recovery rate by crops.

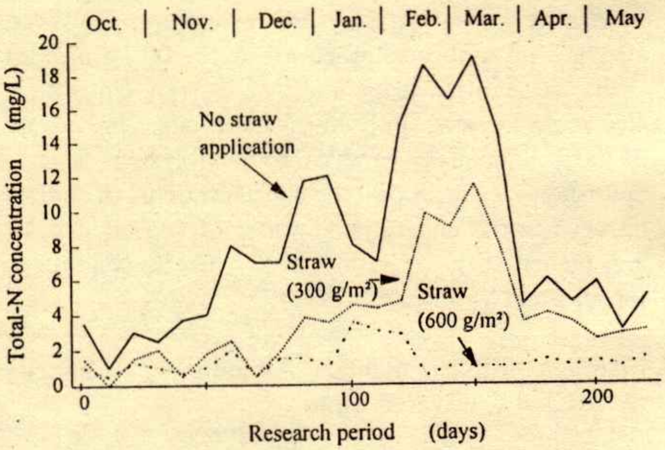

Figure 4. Effect of rice straw application on total-N concentration in permeated water.

Table 3. N recovery rate by crops in each year (%) and secular change.

Prefecture	Crop type	Nitrogen supply †	Year 1976	1977	1979	1980	Average††	Secular change†††
Iwate	Forage	218	42.0	101.3	83.5	218.3	78.1	2.11
		308	34.0	100.0	70.3	104.4	58.1	1.30
	Common	126	85.1	103.0	85.3	87.1	97.0	0.92
		228	60.6	80.3	55.2	30.7	59.3	0.61‡
	Vegetable	288	30.4	63.4	67.2	30.1	59.0	1.04
Yamanashi	Tubers, etc.	271	33.0	113.5	10.9	49.6	54.8	0.41
Ohita	Forage	338	118.4	77.1	115.6	102.5	102.1	1.12
		582	140.4	51.1	142.3	109.2	75.2	1.31
		1136	157.0	71.5	301.4	129.8	58.2	1.89
	Common	147	129.3	167.4	98.0	77.2	128.4	0.59
		393	74.9	70.7	55.7	47.7	70.6	0.71‡
	Vegetable	378	75.5	29.6	74.8	60.4	59.7	1.29

† Yearly average kg ha^{-1}.
†† Average from 1976 to 1980.
††† Secular change (1979+1980)/(1976+1977).
‡ Excess of NEAC.

Table 4. Nitrogen in permeated water (kg ha^{-1}) and secular change.

Prefecture	Crop type	Nitrogen supply †	Year 1976	1977	1979	1980	Average ††	Secular change †††
Iwate	Forage	218	8.0	6.0	3.0	2.0	4.0	0.36
		308	7.0	5.0	5.0	2.0	5.0	0.58
	Common	126	25.0	19.0	88.0	24.0	32.0	2.55
		228	25.0	22.0	88.0	25.0	33.0	2.40
	Vegetable	288	9.0	141.0	21.0	22.0	42.0	0.29
Yamanashi	Tubers, etc.	271	22.0	60.0	277.0	46.0	74.0	3.95
Ohita	Forage	338	26.0	55.0	20.0	78.0	36.0	1.21
		582	82.0	123.0	43.0	65.0	65.0	0.53
		1136	440.0‡	208.0‡	355.0‡	103.0‡	228.0‡	0.71
	Common	147	71.0	22.0	19.0	65.0	43.0	0.90
		393	42.0	43.0	68.0	159.0	63.0	2.67‡
	Vegetable	378	264.0‡	172.0‡	134.0‡	256.0‡	169.0‡	0.89

† Yearly average kg ha^{-1}.
†† Average from 1976 to 1980.
††† Secular change (1979+1980)/(1976+1977).
‡ Excess of NEAC.

NO_3-N L^{-1}. In the plot without rice straw applications, T-N concentration in permeated water increased as the temperature dropped in the beginning of January. T-N concentration was 19.1 mg L^{-1} on February 26. As the temperature rose up, T-N concentration decreased to 4-5 mg L^{-1} in mid-March, the average rate T-N removal was 1.85 kg ha^{-1} d^{-1}. On the other hand, in the plot where 600 g of rice straw m^{-2} was applied, T-N concentrations in permeated water slightly increased for about 3 mg L^{-1} during early January to mid February but kept only about 1 mg L^{-1} during other periods. The average T-N concentration in permeated water was 1.24 mg L^{-1} during the fallow period. We can estimate 591 kg of N was removed in one hectare for 221 days (2.67 kg N ha^{-1} d^{-1}) (Ozaki, 1993). The results of our researches show that rice straw application significantly increase the rate of nitrogen removal even in fallow period.

Utilizing Nitrogen Purifying Capacity of Each Terrain-crop Chain System

Nitrogen purifying capacity of the terrain-crop chain system was studied in which spring water from the tea garden plateau is used as irrigation water to paddy fields through an irrigation pond. Average T-N concentration in the drainage water from the tea garden was 16.6 mg L^{-1} and 92% of that was NO_3-N.

Table 5. Nitrogen-purifying capacity of paddy field (Tabuchi, 1991).

Research area	Land use	N conc. in irrigation water		Nitrogen removal	Remarks
			mg L^{-1}	kg ha^{-1} d^{-1}	
Ibaraki	Rice	Irrigation water	2	0.2	Ogawa and Sakai
(Paddy field)		with animals	7	0.8	May. to Sep.
		urine (T.N)	10	1.3	
			14	1.7	
Ibaraki	Rice	NO_3-N	2	0.8	Ogawa *et al.*
(Paddy field)			6	1.3	May. to Sep.
			12	2.2	
			31	4.9	
Siga	Rice	NH_4-N	8	0.8	Kunimatu *et al.*
(Lysimeter)		NO_3-N	10	1.0	Jun. to Oct.
		NO_3-N	20	1.6	
Ibaraki					Takamura *et al.*
(Lysimeter)	Unplanted	NO_3-N	50	0.8	Sep. to Nov. (Retentive type)
			50	0.4	Nov. to Dec. (Retentive type)
			50	4.2	Sep. to Nov. (Percolating type)
Ibaraki	Unplanted	Spring water	6~12	0.5~4	Tabuchi *et al.* Autumn
(Paddy field)		(T-N)	4~ 8	0.2~2	Winter
			2~ 4	0.7~1.3	Sep. to Nov.

Table 6. NH_4-N concentration in irrigation water and nitrogen-purifying capacity of paddy field in lysimeters †.

NH_4-N Concentration in irrigation water	T-N Inflow ††		T-N Concentration in permeated water ‡		T-N Outflow		Annual T-N removal
	Planted period	Annual (I)	Planted period	Unplanted period	Planted period	Annual (E)	(I-E)
mg L^{-1}	- - - - g m^{-2} - - - -		- - - - - m L^{-1} - - - - -		- - - - g m^{-2} - - - -		g m^{-2}
0	1.53	5.20	0.81	0.48	1.16	2.59	2.61
2	4.36	12.79	0.75	0.46	1.17	2.53	10.26
4	7.03	20.55	0.73	0.64	1.08	2.98	17.57
6	9.73	28.32	0.72	0.65	1.06	2.97	25.35
10	15.30	44.51	0.70	1.43	0.97	5.12	39.39
15	20.34	61.16	2.06	3.54	1.64	12.63	48.53
20	26.73	80.32	1.75	5.89	1.45	19.44	60.88
15 ‡‡	20.34	22.70	1.46	0.50	1.12	2.67	20.03
15 (no planting)	20.13	20.93	4.06	3.17¶	5.19	7.08	13.85

†) Lysimeter dimension = 0.54 X 0.40 X 0.35m. ‡‡) NH_4-N free irrigation water was added during unplanted period.
††) Sum of irrigation and precipitation. ¶) No irrigation water.
‡) Weighted average.

Nitrogen inflow during irrigation was 1 037 kg ha^{-1} (7.92 kg ha^{-1} d^{-1}), and T-N discharge was 910 kg ha^{-1}, resulting in the net removal of 127 kg ha^{-1}. Hence, the average T-N removal rate is 0.97 kg N ha^{-1} d^{-1}. Influent is drained through open ditches during unplanted period of the paddy field, the net removal of T-N during this period is 36 kg ha^{-1} (Table 7). High NO_3-N concentration did not cause lodging of rice, Hasegawa (1992) estimated that the function of paddy fields to remove nitrogen is mainly due to denitrification.

Hidaka and Yamaguchi (1992) also showed changes of NO_3-N concentration in groundwater from upland field in Table 8. Averages of NO_3-N concentration in upland field range from 25.7 to 32.3 mg L^{-1}, but in paddy field range from 1.2 to 2.1 mg L^{-1}.

Table 7. Nitrogen balance in paddy field where drainage from tea garden inflows (Hasegawa, 1992).

Research period	T-N inflow				T-N outflow			Unknown (denitrification)
	Rain	Irrigation water	Fertilizer	Total	Uptake by rice	Surface drainage	Total	
	kg ha^{-1}				kg ha^{-1}			
Planted period	7.0	1 030	64	1 101	69	910	979	122
Unplanted period	6.0	950	-	956	-	920	920	36
Annual	13.0	1 980	64	2 057	69	1 830	1 899	158

1) Planted period: Apr. 22~Aug. 30 (131 days). 2) Unplanted period: Aug. 31~Apr. 21 (234 days).
3) Straw (47 kg N ha^{-1}) is not included in the absorption by rice because it is incorporated into the soil.

Table 8. Changes of NO_3-N concentration in ground water from upland to paddy field (Hidaka, 1990).

Sampling site	NO_3-N concentration						Elevation above sea level
	7/10	7/23	8/18	10/22	12/5	Aver-age	
	mg L^{-1}						m
Upland field 1 (WW)	27.5	27.0	44.4	32.5	30.3	32.3	45
Upland field 2 (WW)	23.7	23.4	20.6	29.8	31.7	25.9	41
Upland field 3 (SW)	23.4	23.1	23.6	29.0	29.2	25.7	40
Upland field 4 (SW)	25.8	25.2	24.9	31.7	32.0	27.9	38
Upland field 5 (SW)	24.5	23.8	24.7	29.6	31.7	26.8	38
Upland field 6 (SW)	23.4	23.0	25.9	28.3	59.1	32.0	35
Paddy field 1 (WW)	7.2	1.1	1.2	0.6	0.6	2.1	35
Paddy field 2 (SW)	2.4	1.0	0.0	0.1	-	1.2	35

WW = Well water, SW = Spring water.

These results show that we can utilize the nitrogen purifying function of each terraincrop chain system, such as tea garden or vegetable fields to paddy field, to control NO_3-N concentration in groundwater.

To Promote Benefit Use of Organic Waste

To expand beneficial use of organic waste we have to understand advantages and disadvantages of organic waste.

Annaka and Oshima (1988), Chino (1993) and Kurihara (1993) summarized advantages and disadvantages of organic waste compared with chemical fertilizer in Japan as follows.

Advantages. (1) Low price. (2) Slow release nitrogen. (3) Rich in available micronutrients. (4) Neutralizing power of soil acidity (limed sewage sludge) and avoiding function of over liming in green house soil (polymer used sewage sludge). (5) Increasing power of organic carbon contents and improving power of soil physical properties.

Disadvantages. (1) Noxious odor. (2) Unstable supply. (3) Difficulty in mechanical spreading. (4) High content of heavy metal. (5) Anxiety about quality change during storage. (6) Regionally uneven distribution.

To decrease disadvantages and to increase advantages of organic waste, composting is essential. Harada *et al.* (1993) summarized objectives of composting as follows: (1) To increase handling quality and safety for health and to decrease noxious odor. (2) To convert organic waste into organic materials or organic fertilizers which are safe for plant and soil micro-organisms.

To expand beneficial use, followings are essential. (1) Improvement of quality and performance, such as granulation, increase of potassium and magnesium contents, decrease of heavy metal concentration. (2) Development in use of organic waste compost to newly expanding crops such as flowers. (3) Innovation of farmers' and food consumers' consciousness on the use of organic waste compost for food crop lands. (4) Information service on component and heavy metal concentration in organic waste compost, and also information service on stocking amount of compost and local utilization system. (5) Settlement of open fields applied with organic waste compost for exhibition and long term monitoring of heavy metal concentrations in edible parts of crops and in soils (Annaka and Oshima, 1988; Chino, 1993; Chino *et al.*, 1992; Kurihara, 1993).

New Trends of Beneficial Use of Sewage Sludge for Green and Agriculture

Yokohama city developed granulated artificial horticulture medium'Hamasoir' from sewage sludge ash. They are now testing the function of this medium

Table 9. Chemical properties of Hamasoiru.

Element	Concentration	
N, P_2O_5, K_2O, CaO	280, 1200,	100, 1100
	- - - - mg kg^{-1} - - - -	
Properties	Hamasoil	Natural
Electric conductivity (mS cm^{-1})	0.8 - 1.2	0.5 - 1.2
Cation-exchange capacity (meq kg^{-1})	150 - 200	200 - 400

and developing a new cultivating technology for flowers (Hakuyusha, 1991). This granulated horticulture medium is made from incinerated ash of polymer used sewage sludge and poly-vinyl-alcohol.

Table 9 shows chemical properties of this medium. It has excellent physical properties, such as water stable aggregate, enough water retentivity and air permeability, and also has good sanitary and safe condition for human health. Furthermore, we can easily know the time of water supplying to this medium because of color change.

Artificial culture medium like this may provide a big market for sewage sludge in urban area.

Sapporo city began to provide granulated sewage sludge compost in 1991 (Kawanishi and Iida, 1992). They produce three kinds of granulated compost by sieving, less than 1 mm, 1-5 mm and bigger than 5 mm in diameter. There are 5-kg bags, 20-kg bags and 500-kg packs in the form of goods. They set price at 300 yen for one 20-kg bag of 1 mm compost and 400 yen for one 20-kg bag of 1-5 mm compost. The sales of compost have been steady with increase. Farmers use this compost to various crops, such as wheat, grasses, vegetables, onion, red bean, etc. Table 10 shows concentration of nutritious elements and heavy metals in Sapporo Sewage Sludge Compost. Concentrations of heavy metals are lower enough than the standard settled by National Environment Agency.

Heavy Metal Concentration in Sewage Sludge Compost and Soil Micro-organisms Activity in Various Kinds of Soil

Sewage sludge compost usually has higher heavy metal concentration compared with crop residue compost (Table 11) (Kurihara, 1993). Therefore, concentration of heavy metal in sewage sludge compost for agricultural land use has to meet the standards according to the Fertilizers Control Law shown in Table 12 (Hakuyusha, 1991). Concentration standards

Table 10. Analyses of Sapporo compost (based on dry solids).

Element	Range	Average	Element	Range	Average	Standard†
	%			mg kg^{-1}		
T-N	2.19- 2.44	2.30	Hg	0.34- 0.51	0.43	2
P_2O_5	2.98- 3.47	3.25	Cd	0.78- 1.37	1.17	5
K_2O	0.14- 0.19	0.16	As	5.96- 8.52	7.24	50
CaO	18.4 -20.4	19.5	Ni	22.0 - 30.9	24.9	-
MgO	0.63- 0.74	6.67	Cu	99.0 - 120	112	-
T-C	21.8 -24.2	23.2	Zn	470 - 566	527	-
H_2O	18.5 -21.7	20.1				

† Toxic Substances Standard of Special Fertilizer in the Fertilizer Control Law of Japan.

Table 11. Heavy metal concentration in sewage sludge compost and crop residue compost.

Element	Sewage sludge compost		Crop residue compost	
	Range	Average	Range	Average
	mg kg^{-1}		mg kg^{-1}	
Hg	0.03 - 3.30	1.37	0.01- 0.32	0.11
Cd	0.01 - 6.86	2.79	0.02- 2.90	0.82
As	0.07 - 16.1	4.55	0.01- 4.38	2.22
Cu	3.0 - 680	184	2.0 - 62.0	28.0
Zn	167 - 3320	1110	15.0- 222	82.0

Table 12. Maximum permission concentration of heavy metal in sewage sludge for agricultural utilization (mg kg^{-1}, based on dried solid).

Element	Belgium	Denmark	France	Germany	Netherlands	U.K	Switzerland	Japan
Hg	10	6	10	25	5	7.5	10	2
Cd	10	0	20	20	5	20	30	5
As	10				10			50
Cu	500		1000	1200	600	1500	1000	
Zn	2000		3000	3000	2000	2000	3000	

of heavy metal in sewage sludge in Japan are rather strict compared with those of the other countries except As (Table 12). To establish standards of Zn and Cu concentration in sewage sludge compost and sewage sludge fertilizer, investigation is now undergoing in Japan.

Besides of heavy metal concentration in sewage sludge compost, concentration of heavy metal in soil, represented by Zn, has to meet the management standard as shown in Table 13.

Detail surveys revealed that the Zn concentration in the soil derived from Fuji Volcanic Ash of Japan is very high. Averages of Zn concentration in Tokyo and Kanagawa are 119 mg kg^{-1}. This value is as high as the Zn concentration standard 120 mg kg^{-1}.

Soil microbial thermo-analyzing is an excellent method to evaluate the activity of soil micro-

Table 13. Management standards for heavy metals in sewage sludge applied to agricultural land (Notice by the Department of Water Conservation. Environment Agency).

1. The index for controlling accumulation of heavy metals in the soil of agricultural land shall be zinc content.
2. The management guideline relating to controlling accumulation of heavy metals in the soil of agricultural land shall be **120 mg of zinc** per 1 kg of dry soil.
3. The analytical method to measure the zinc content in the surface soil shall be the atomic absorption spectrophotometry following the **digestion by mineral acids**.

Table 14. Chemical properties of soil samples.

Soil	pH(1:5)	EC(1:5)	CEC		T-C	T-N	C/N	Zn
			pH7.0	pH5.0				
			me/100g		- - - - - %	- - - - -		mg kg^{-1}
Volcanic 1	5.8	0.213	18.6	9.0	3.53	0.460	7.7	73
Volcanic 2	6.1	0.278	-	-	5.24	0.600	8.7	81
Granite	5.6	0.064	9.5	5.5	1.20	0.234	5.1	32
Alluvial	5.6	0.110	10.7	6.9	1.60	0.278	5.8	67

Amount of compost applied to Volcanic 1 and 2 soil is 0 and 4 t yr^{-1}.

Table 15. Chemical properties of sewage sludge samples.

No.	Froccul	pH (H_2O)	T-C	T-N	C/N	Zn
			%	%		mg kg^{-1}
101	Hi-poly	6.5	34.7	6.4	5.4	2050
102	Inorgan	10.0	20.5	2.2	9.3	1430

Table 16. Estimated critical levels of Zn concentration in soil to micro-organisms activity (mg kg^{-1}).

Type of S.S. added	Volcanic1	Volcanic 2	Granite	Alluvial
No addition	118 - 163	126 - 177	77 - 122	122 - 157
Lined S.S.	133 - 178	141 - 186	92 - 137	127 - 172
Hi-Polymer S.S.	126 - 171	(179 - 224)	85 - 122	120 - 165
Summarized	133 - 163	141 - 177	92 - 122	127 - 157

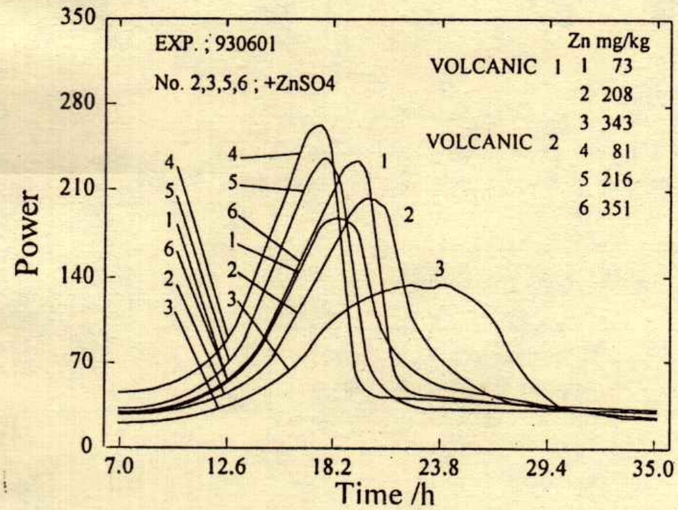

Figure 5. Growth curves of micro-organisms in volcanic ash soil samples.

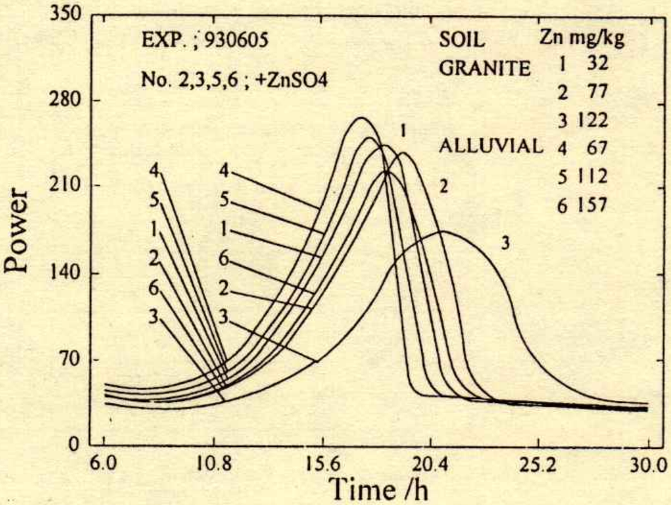

Figure 6. Growth curves of micro-organisms in granite and alluvial soil samples.

organisms. We made some experiments with sewage sludge to check the relationship between Zn concentration and growth rate of soil micro-organisms, and estimated the critical level of Zn concentration that effects growth rate of soil micro-organisms. Table 14 shows some chemical priorities of soil samples, and Table 15 shows those of sewage sludge samples. As shown in Figures 5 and 6, Zn concentrations that decrease the growth rate of soil micro-organisms are different in each kind of soil. Table 16 shows estimated critical levels of Zn concentration. The critical level in granite soil is the lowest and that in volcanic ash soil 2 is the highest, and critical levels of alluvial and volcanic ash soils are higher than the Zn concentration standard 120 mg kg^{-1}.

We estimated these critical levels under the most strict conditions that means just or 1-day incubation after addition of $ZnSO_4$ to increase Zn concentration in soil samples. Hattori (1989; 1992) showed toxicity of Zn in soil decreases after long incubation. Soil micro-organisms activity may be affected by the concentration of water soluble Zn not by strong acid soluble Zn.

CONCLUSIONS

Minami (1993) indicated that rice cropping which utilizes terrain-crop chain is an ideal agricultural system in Japan because it needs the least labor and energy, maintains continuous production and preserves the environment. We propose plans in Figure 7, for

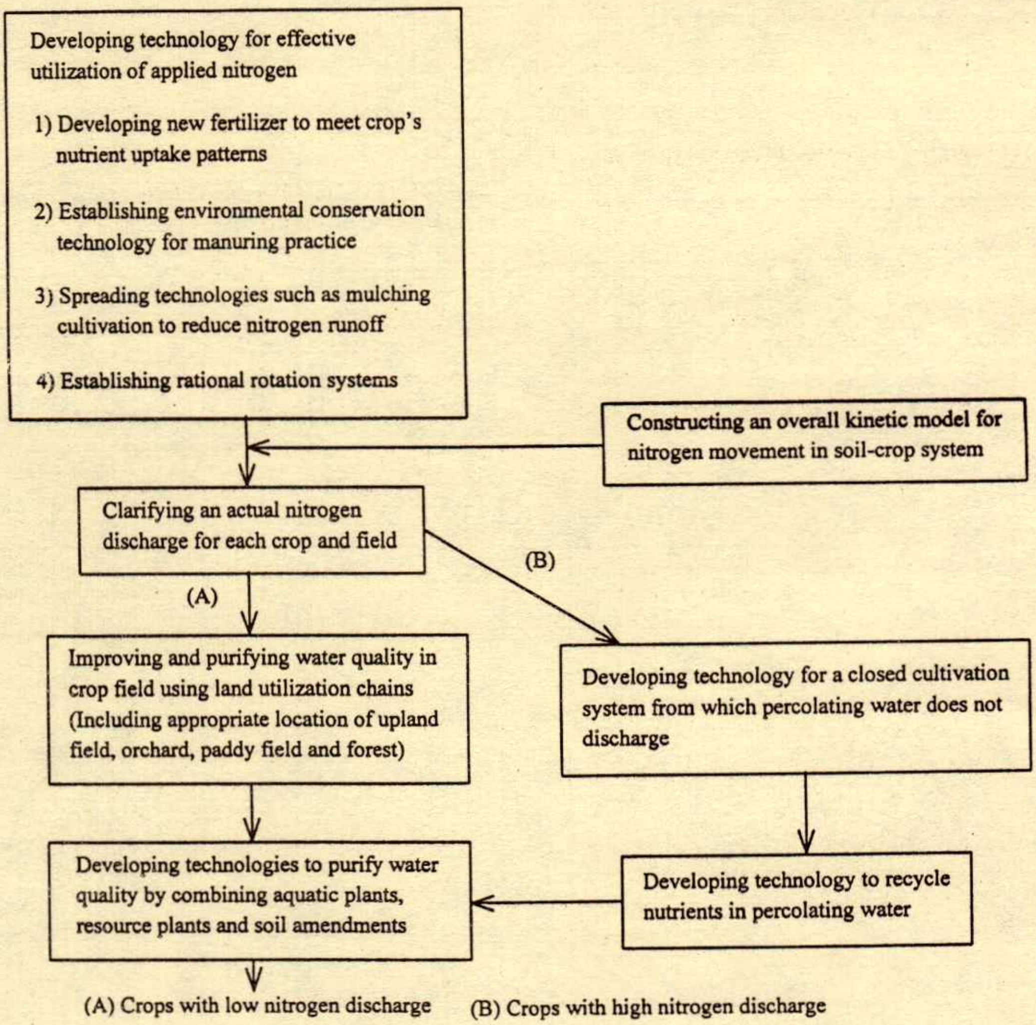

Figure 7. Proposed measures for reducing nitrogen discharge from upland field and future plan for managing water quality in agricultural watershed.

reducing N load and for water-quality control. The first plan is to increase utilization efficiency of applied N (including manure) and to balance nitrogen application and uptake for each field. The second is to develop a synthetic model for nitrogen movement in a soil crop chain system and to use this model to control nitrogen flow to plans and the environment. The third is to develop technologies for improving and purifying water quality within an agricultural watershed utilizing the water purification capacity of a terrain-crop system. The fourth is to develop cultivation technologies within each closed system from which permeated water does not flow out, and to establish technologies for recycling manure components for regions where water quality is not sufficiently improved by the above three methods, such as regions of protected horticulture and animal husbandry. The final is to establish and expand a system which exhaustively recycle manure components, such as nitrogen, within the field.

Agriculture is the only industry that originally has the function recycling material. Beneficial use of organic waste compost has to be expanded with the environmental assimilating capacity in one field or in every water system.

Long term open fields for exhibition to the public and for monitoring of heavy metal contents in edible part of crop and in soil will be of great help to expand consumption of organic waste compost for greens and agricultural land.

Artificial culture medium made from organic waste ash may help greatly to expand consumption of organic waste in urban area. Granulated organic waste compost with high quality and low concentration of heavy metals is expanding consumption of sewage sludge in rural area.

Soil micro-organism carries the function recycling material. It is one of the most important components that decide environmental assimilating capacity. Monitoring of soil with the method of soil micro-organisms activity may be useful to review too much strict management standard of heavy metal concentration in soil of agricultural land.

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ROLE OF GRAIN LEGUMES IN NITROGEN CYCLING OF LOW INPUT SUSTAINABLE AGROECOSYSTEMS

Papel de las Leguminosas de Grano en el Ciclaje de Nitrógeno de los Agroecosistemas Sostenibles de Bajos Insumos

E. S. Jensen[1] and J.Z. Castellanos [2]

SUMMARY

Grain legumes are important food and feed protein sources and contribute N to agroecosystems via symbiotic N_2-fixation. If major environmental constraints are alleviated, grain legumes may fix high amounts of N and produce high seed yields. Intercropping of grain legumes and cereals may improve the overall resource utilization and minimize risks of crop failure. However, it is important to manage grain legumes in order to conserve the symbiotically fixed N within the soil-plant system and reduce N losses due to leaching. We focus on the role of grain legumes in N cycling of low input sustainable agroecosystems using common bean (*Phaseolus vulgaris* L.) and field pea (*Pisum sativum* L.) as cases.

Index words: Phaseolus vulgaris *L.*, Pisum sativum *L., N fixation.*

RESUMEN

Las leguminosas de grano son una fuente importante de alimento y fuente de proteínas que contribuyen con nitrógeno a los agroecosistemas via fijación simbiótica de nitrógeno. Si las principales limitantes ambientales son reducidas, las leguminosas de grano pueden fijar grandes cantidades de nitrógeno y producir alto rendimiento de semilla. Los cultivos intercalados de leguminosas y cereales pueden mejorar la utilización total de los recursos y minimizar el riesgo de la producción de granos. No obstante, es importante manejar las leguminosas de grano para poder conservar el nitrógeno fijado simbióticamente dentro del sistema de cultivo y reducir las pérdidas de nitrógeno debidas a la lixiviación. En este trabajo, nos enfocamos al rol de las leguminosas de grano sobre el ciclo de nitrógeno, en los agroecosistemas sustentables de bajos insumos usando el frijol (*Phaseolus vulgaris* L.) y el chícharo (*Pisum sativum* L.) como casos específicos.

Palabras clave: Phaseolus vulgaris *L.*, Pisum sativum *L., fijación de N.*

INTRODUCTION

Agricultural sustainability is defined as: "The successful management of resources to satisfy changing human needs while maintaining or enhancing the quality of the environment and conserving resources" (Bohlool *et al.*, 1992). The central aim of low input sustainable agriculture in developing and industrialized countries is to achieve long-term stabilization of agricultural production without or with only limited use of nonrenewable energy sources, fertilizers, and agrochemicals.

Since plant nutrients are lost from the farm by human consumption, export of products and losses in the field, inputs of major plant nutrients are necessary to maintain the production and soil fertility. Nitrogen (N) is often a major limiting factor in plant production, and N-deficiency may be alleviated by the use of N-fertilizers. However, there are vast areas of the developing world where N fertilizers are neither available nor affordable. In the industrialized countries there is an increasing interest in developing more energy-efficient and sustainable agriculture systems, e.g. organic farming systems, without the use of fertilizer and agrochemicals in order to reduce surplus production and environmental problems due to intensive agricultural methods. Biological N_2-fixation in symbiotic relationships involving legumes and *Rhizobium* spp. offers an economically attractive and ecologically sound means of reducing external inputs

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of N and improves the quality and quantity of internal sources (Bohlool *et al.*, 1992).

Grain legumes, such as soybean (*Glycine max* L. Merr.), common bean (*Phaseolus vulgaris* L.), and field pea (*Pisum sativum* L.), provide a protein-rich source of human food and animal feed. The world area, total production and average yield per hectare of the seven most important grain legumes are shown in Table 1. The total grain production of these seven legumes contains about $9x10^6$ metric ton of N. Assuming an average nitrogen harvest index (proportion of total N in grain) of 0.7 and about 50 % of N in the crop being derived from fixation, it is estimated that a total of $6.4x10^6$ ton of N are fixed annually by these legumes. This represents approximately 10 % of the N input from N fertilizers (Paul, 1988).

Since grain legumes are grown for harvesting the seed, it is desirable to maximize the seed dry matter and N yield. Thus, only a minor proportion of the N_2 fixed by grain legumes may contribute to soil fertility and the N-nutrition of inter- or subsequent crops. If legume grains are used as animal feed, a major part of the fixed N may be recycled via animal manure (Henzell and Vallis, 1977).

The aim of this work is to evaluate the role of grain legume crops in the N cycling of low input sustainable agroecosystems. We will focus on each of the three components of the sustainability issue: production, resource conservation and environmental quality and evaluate in which way grain legume crops and their management may contribute to the sustainability of agroecosystems. Common bean (*Phaseolus vulgaris* L.) and field pea (*Pisum sativun* L.) are chosen as cases to represent grain legumes grown in tropical-subtropical and temperate regions, respectively.

Common Bean and Field Pea Grain Production

Common bean (*Phaseolus vulgaris* L.) is a major crop in Latin America and Africa (Giller and Wilson, 1991), but the crop is also grown in temperate regions. Common bean is mainly grown for harvest at the dry seed stage. The fertility of soil relegated to common bean production vary greatly in pH and major and minor elements, from inadequate amounts to levels toxic to plants and *Rhizobium* (Bliss, 1993). Accordingly, the yield of the common bean crop is extremely variable and besides soil fertility, yields are

Table 1. World area, average yield and total production of seven important grain legumes. (FAO, 1991)

Grain legume	Area	Average yield	Total production
	10^6 ha	t ha^{-1}	10^6 t
Soybean	55.4	1.86	103.1
Common bean	26.3	0.66	17.5
Peanut	20.3	1.15	23.4
Chickpea	10.8	0.72	7.7
Field pea	9.3	1.76	16.3
Fababean	3.2	1.43	4.5
Lentil	3.1	0.76	2.4

influenced by e.g. cultivar (Rennie and Kemp, 1983a, b), *Rhizobium* inoculation (Thies *et al.*, 1991a, b) and irrigation (Peña-Cabriales and Castellanos, 1993) with yields ranging from <0.5 to near 5 t ha^{-1} (Castellanos, 1992). Field pea (*Pisum sativum* L.) is a cool-season crop that grows best between 10 °C and 30 °C and it is consequently largely confined to temperate regions for production of dry seeds. In Europe field pea is grown primarily as a "break-crop" in cereal rich rotations, e.g. preceding winterwheat. The world average yield of dry pea is about 1.8 t ha^{-1} (FAO, 1991). In North-Western Europe pea is normally grown in fertile soil and yields may exceed 5 t seed and 1.5 t protein ha^{-1} (Jensen, 1989). On these soils water is one of the major limiting factors on grain yield. Water stress during reproductive growth stages may reduce yields significantly (Jensen, 1987).

The harvest index (HI) of a crop expresses the proportion of grain dry matter of total aboveground dry matter production. In a well-adapted common bean cultivar grown under non-stress conditions HI range from 0.40 to 0.55 (Castellanos, 1992). Similar values are found in field pea (Beck *et al.*, 1991; Jensen *et al.*, 1985). The higher the HI of a grain legume crop, the lower is the amount of crop residues, which may be used as animal feed or as a C and N source for increasing levels of soil organic matter.

Intercropping. Intercropping of plant species is a common practice in large parts of the world, especially in low input agricultural systems of the tropics. Previously intercropping was also a common practice in industrialized countries, but the intensification of agricultural plant production with the use of fertilizers, agrochemicals and heavy machinery have gradually eliminated intercropping. Now, intercropping is mainly practiced in clover-grass leys. However, intercropping is an integrated part of sustainable farming systems, since intercropping may result in a higher combined yield than if each of the components were grown in pure stands on the same piece of land, improves the use of resources and minimizes risks due to plant diseases and insects (Trenbath, 1976).

In many areas of Latin America common bean has traditionally been intercropped with maize (Francis *et al.*, 1976), and experiments have shown that the yield and the overall resource use may be more than 60 % higher in intercrops compared to pure stands (Faris *et al.*, 1983; Santa-Cecilia and Vieira, 1978). Field pea is normally grown in pure stand, but experiments with intercrops of pea and cereals have shown an improved utilization of resources, especially of N, more stable yields than of pure stand pea and in many cases higher yield of the mixtures than each of the pure stands at low levels of N-fertilization (Cowell *et al.*, 1989; Jensen *et al.*, 1985). Jensen *et al.* (1985) found that the yield of a 1:1 mixture of pea and barley produced the same grain yield without N-fertilization (5.2 t ha^{-1}) as pure stand barley fertilized with 80 kg N ha^{-1}. The protein yield was 30 % higher in the intercrop than in the N-fertilized barley crop. However, the protein yield of an intercrop may not be higher than the protein yield of the grain legume grown, since non-legumes have lower N concentrations and may be more competitive for most growth factors (Cowell *et al.*, 1989; Jensen *et al.*, 1985).

Resource Conservation and Grain Legume Cultivation

The cultivation of grain legumes, fixing N_2 in symbiosis with *Rhizobium*, contributes to the N-sustainability of an agricultural system, since N fixed by the legume can be viewed as a "free" resource. Nitrogen fixation occurs as a consequence of capture of the energy of continuously renewable sunlight in the photoassimilates of green plants (Heichel, 1987). The alternatives to substituting the N-losses and maintaining soil N fertility in agricultural systems are organic manure or N-fertilizer. Synthesis of N-fertilizer requires the use of large amounts of non-renewable energy resources. The energy requirement for the production, transport and application of 1 kg of fertilizer N is approximately 78 MJ corresponding to about 1.2 m^3 natural gas or 2l Diesel-oil (Mudahar and Hignett, 1987). On the other hand, the grain legumes take up soil N, of which the major part is removed by seeds and the remaining is recycled. Depending on the balance between N_2-fixation and seed N removed, grain legumes may either diminish or increase the soil N resources.

N_2 fixation by common bean and field pea. The cultivation of beans on poor soil (Tsai *et al.*, 1993a, b) or under water stress (Castellanos, 1992) have resulted in the general supposition that *P. vulgaris* is a poor N_2 fixing plant, which requires fertilizer N to produce acceptable yields (Müller *et al.*, 1993). In many experiments inoculation with *Rhizobium* neither improved the nodulation nor the yields, indicating that some environmental constraint is limiting yields (Giller and Wilson, 1991). Experiments carried out under the FAO/IAEA Coordinated programme: "Enhancement of Biological Nitrogen Fixation of Common Bean in Latin America", have shown that if environmental conditions are optimized, including the inoculation with efficient strains of *Rhizobium*, plants nodulate and fix enough N_2 to support grain yield of up to 2 t ha^{-1} (Bliss, 1993). (Thies *et al.*, 1991a, b) evaluated the response to inoculation in several grain legumes and they reported that the native populations of *Rhizobium* and the potentially available N were the two main factors affecting the response to inoculation. Since Mexico is a centre of origin of common bean, native populations of *Rhizobium* are abundant. This is probably the reason for the low rate of inoculation response found in common bean in Mexico (Castellanos, 1992). More information on N_2-fixation by common bean in fertile soils with native populations of *Rhizobium* would be valuable. In soils without native populations of *Rhizobium* for common bean, the introduction of efficient strains, which can persist in the soil under adverse environmental conditions, appears to be a more sustainable approach than the inoculation of each crop. Field pea is nodulated readily in most soils and do not respond to inoculation with *Rhizobium* and N-fertilization (Jensen, 1986; 1987a, b). Most soils of North-Western Europe contain native and persistent populations of efficient *Rhizobium* strains, which nodulate field pea.

Common bean and field pea have been reported to be able to fix more than 150 and 200 kg N ha^{-1}, respectively (Hardarson *et al.*, 1993; Jensen, 1986). Table 2 summarizes data on N_2-fixation and soil N uptake in common bean and field pea. Both pea and common bean N_2-fixation is influenced by cultivar (Table 2). The N_2-fixation by grain legumes are

Table 2. Seasonal N_2-fixation and soil N uptake in common bean and field pea determined by ^{15}N isotope dilution techniques.

Species/ location	Treatment variable	Total N	% N dfa†	N_2-fixation	Soil N uptake	Reference
		kg N ha^{-1}		kg N ha^{-1}	kg N ha^{-1}	
Common bean						
Brazil	Cultivar	60-101	38-65	25-65	23-40	Ruschel *et al.*, 1982
Kenya	Nitrogen	175-195	11-45	21-78	154-117	Ssali and Keya, 1985
Austria	Genotype	62-290	27-67	25-165	30-136	Hardarson *et al.*, 1993
Brazil	Genotype	40-50	12-25	4-12	35-40	Hardarson *et al.*, 1993
Mexico	Genotype	98-200	5-58	7-108	50-130	Hardarson *et al.*, 1993
Mexico	Water	77-148	0-57	0-85	63-77	Castellanos, 1992
Canada	Cultivar	100-182	38-68	40-125	52-75	Rennie and Kemp, 1983
Canada	Stain	130-238	0-73	0-121	35-178	Rennie and Kemp, 1983
Field pea						
Sweden	Cultivar	230-231	53-62	122-145	86-108	Haak, 1983
Denmark	Cult., year	226-337	43-64	102-215	68-94	Jensen, 1986
Canada	Cult., site	216-236	75-82	166-189	40-58	Rennie and Dubetz, 1986
USA	Site, year	116-140	45-62	63-76	46-77	Smith *et al.*, 1987
Australia	Site, year	61-191	20-95	28-177	29-111	Evans *et al.*, 1989
Canada	Pure stand	25-109	28-80	20-50	5-70	Cowell *et al.*, 1989
	Intercrop	18-82	33-88	16-27	2-55	
Denmark	Pure stand	242-338	53-64	128-245	91-118	Jensen *et al.*, 1985
	Intercrop‡	34-88	79-82	27-71	5-15	

† % Ndfa: % of total crop N derived from N_2-fixation.
‡ Intercrop of field pea and barley, each sown at 50 % of the pure stand density.

influenced by crop management practices and environment, e.g. alleviation of water stress during reproductive growth stages seems to be an important factor in determining levels of N_2-fixation in both crops (Evans *et al.*, 1989; Jensen, 1987; O'Connor *et al.*, 1993; Peña-Cabriales and Castellanos, 1993). The major effort to increase symbiotic N_2-fixation by grain legumes has been devoted to the microsymbiont eventhough great genotypic variability has been shown in e.g. common bean (Rennie and Kemp, 1983a, b). Castellanos (1992) found that bean lines with a long vegetative growth period had a high N_2 fixing capacity. Bliss (1993) described the methodology to develop genotypes with high N_2 fixing capacity and states that this trait should be as important as yield or improved pest tolerance in breeding programmes.

Intercropping grain legumes with a cereal may significantly reduce the amount of N_2 fixed per ha since the number of plants per unit area is reduced and because competition for other growth factors than N in the intercrop may depress the growth of pea (Table 2; Jensen *et al.*, 1985). Since grain legume cultivars may respond differently to competition from an associated cereal, it would be valuable to select cultivars for suitability as an intercrop (Francis *et al.*, 1976; Tsai *et al.*, 1993b).

Soil N uptake by common bean and field pea. Depending on the level of soil mineral N and the cultivar, the contribution from N_2-fixation to N total plant may vary between 20 to 60 % in common bean and 40 to 70 % in field pea (Table 2). The remaining crop N is derived from the soil mineral N pool. Soil N taken up by the grain legume crop is either removed with the harvested seed or recycled to the soil via crop residues. Without N-fertilization the available soil N is derived from mineralization of soil organic matter and atmospheric deposition. In order to increase the sustainability of an agricultural system, the mineral soil N must be used efficiently in the plant production. If levels of mineral soil N are high during periods with fallow or newly planted soil, there is a risk that N is lost by leaching or denitrification. Soil N taken up by a grain legume plant is conserved, but from a resource use point of view it is inefficient use of soil N, since legumes can fix their own N. High levels of soil N may even reduce N_2-fixation by the legumes. Environmental stress such as mild drought may increase the proportion of total N in plants being derived from soil N and also the amount of soil N taken up (Castellanos, 1992).

Very large differences in the soil N uptake by both common bean and pea cultivars are obvious from the

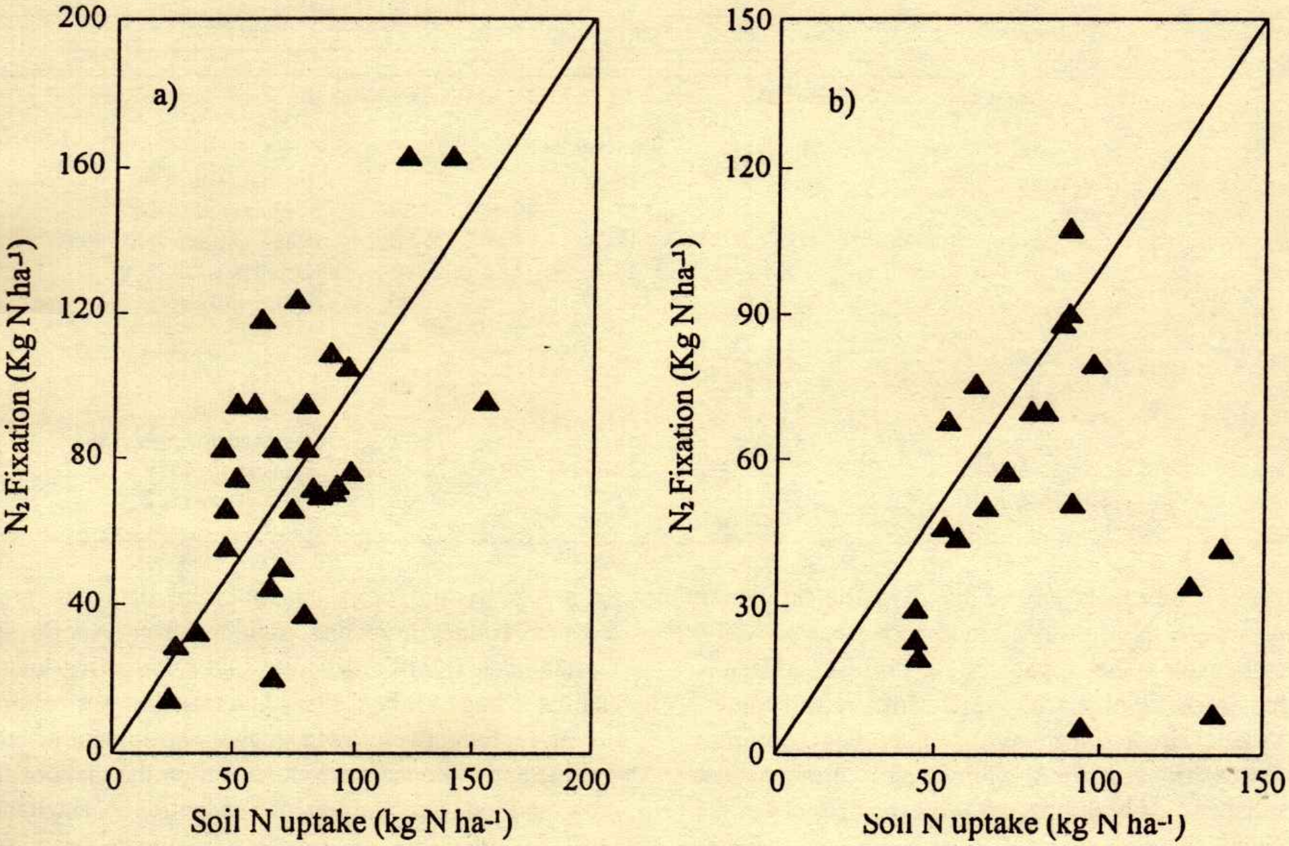

Figure 1. Relationship between soil N uptake and N_2-fixation in common bean genotypes. Data: experiment from Austria (a) and Irapuato, Mexico (b) (Hardarson *et al.*, 1993).

data in Table 2. A cultivar which is efficient in taking up soil N may fix less N_2 than a cultivar which is not that efficient in acquiring soil N. However, such relationship does not seem to be obvious from Figure 1, which shows data from experiments carried out in Austria and Mexico to determine N_2-fixation in different genotypes of common bean (Hardarson *et al.*, 1993). In the Austrian experiment there was a tendency towards a positive correlation between soil N uptake and N_2-fixation. The data revealed that besides a large genotype effect on N_2-fixation the soil N uptake varied between 27-153 kg N ha^{-1}. The results showed that cultivars which took up about 70 kg N ha^{-1} the fixed N varied between 25-125 kg N ha^{-1} (Figure 1a).

The Mexican data indicated that the higher the soil N uptake in common bean the lower is the N_2-fixation (Figure 1b). The Mexican data also revealed a large variation in soil N uptake capacity by common bean. A cultivar which is inefficient in taking up soil N may be useful in an intercrop, but in pure stand there would be a high risk of losing soil N by leaching. Thus, from a resource use point of view a cultivar with a high N_2-fixation capacity and a low soil N uptake capacity would be useful in the intercrop situation. In a region of high risk of nitrate leaching such a cultivar would not be recommendable to be grown in pure stand due to the potential risk of losses of N from the farming system. On the other hand, it is convenient to have cultivars with high N_2-fixation capacity and low soil uptake in a semiarid region with little risk of nitrate leaching. Here, spared soil N can be utilized by subsequent crops. In breeding of grain legumes one should not focus on yield and N_2-fixation alone, but also take the capacity soil N uptake into account.

Even if grain legume may take up high amounts of soil N, the soil profile usually contains higher levels of soil mineral N, especially below the ploughlayer, after grain legumes than after cereals (Evans *et al.*, 1991; Jensen, 1989; Jensen and Haahr, 1990). The reasons for the higher level of mineral N in soil after grain

Table 3. Grain yield, N content of aboveground residues and N harvest index (NHI) for common bean and field pea.

Species/ Location	Treatment variable	Grain yield	Aboveground residue	NHI	Reference
		t ha^{-1}	N kg ha^{-1}	%	
Common bean					
USA	Cultivars	1.7-3.1	5-88	72-95	Piha and Munns, 1987
Brazil	Cultivars	0.3-0.9	46-68	13-32	Ruschel *et al.*, 1982
USA	Lines		13-30	76-89	St.Clair *et al.*, 1988
Mexico	Cultivars		18-32	76-88	Peña-Cabriales *et al.*, 1993
Mexico	Cultivars	2.8-4.7	20-50	47-80	Castellanos, 1992
Canada		3.3	32	79	Kucey, 1989
Field pea					
Denmark	Pure stand	5.3	75	73	Jensen *et al.*, 1985
	Intercrop	1.2	7	83	
Denmark	Season	2.0-6.4	32-92		Jensen, 1989
Canada	Cultivar	3.6-3.9	52-56	71-72	Rennie and Dubetz, 1986
Australia	Site, season		33-111	28-63	Evans *et al.*, 1989
USA	Site, season	1.4-2.4	41-73	40-65	Smith *et al.*, 1987
Canada		6.3	115	66	Kjellerup, 1991

legumes is not clear. It may be due to inefficient uptake of soil mineral N, due to a small root system, which can only exploit the upper soil layers. The effect is referred to as a "N-sparing" effect of grain legumes. The high levels of soil mineral N may also be due to differences between grain legumes and cereals in net mineralization of N during the turnover of roots in the reproductive growth stages. Grain legume root residues have higher N concentrations than cereal root residues, and a higher deposition of N in the rhizosphere may result in higher net mineralization of N after legumes. Soil mineral N present after harvest of grain legumes can contribute to the subsequent crop or it may be lost by leaching. In temperate regions with high rainfall in the autumn there is a high risk that this N is lost by leaching even if the soil is planted to winterwheat and winterbarley succeeding a pea crop do not have the capacity to take up all the "spared" soil N, which is often found after grain legumes, whereas winter oilseed rape seems to me much more efficient in recovering soil mineral N in the autumn (Jensen and Haahr, 1990).

Crop residues returned to soil. Grain legume crop residues contain higher amounts of N than cereal crop residues. However, a grain legume crop is considered N sustainable only when the proportion of N in the crop derived from fixation is equal to or higher than the proportion of plant N harvested in seed (N-harvest index, NHI) or otherwise removed from the field. In other words, the amount of N recycled to the field in residues must be higher than the amount of soil N taken up by the crop. Quantitative data for grain legume residues are often excluded from reports and measurements are difficult and normally underestimated due to fallen leaves and the turn over of roots during reproductive growth stages. The amount of crop residue and N concentration depend on the yield of the crop and on the reproductive adaption. Castellanos (1992) studied 68 cultivars of common bean and reported the following averages: grain yield 2.7 t ha^{-1}; crop residues 2.7 t ha^{-1}; aboveground residue N 35 kg N ha^{-1}; N concentration residues 1.3 % N. Table 3 summarizes data on crop residues for common bean and field pea. The N harvest index varied typically from 70 % to 90 % in common bean and 60 % to 70 % in field pea, and amounts of N in above-ground residues were found up to 88 kg N ha^{-1} in bean and 115 kg N ha^{-1} in pea. Only a few reports are available on root residues, and amounts of root N harvested at maturity are usually below 5-10 kg N ha^{-1} (Jensen,1989; St. Clair *et al.*, 1988).

Since grain legumes are grown for harvest of the dry seeds, breeding of these plants has focused on developing genotypes with high efficiency to translocate N and carbohydrates to grains. Breeders could revert from this goal and breed for genotypes with lower harvest and N-harvest indexes provided that the yield level is not lowered. Such genotypes would contribute more N and C to soil and increase the value of the crop in maintaining soil fertility. The recently registered common bean genotype "Flor de Mayo M-38" (Acosta-Gallegos *et al.*, 1994) has a harvest index of about 0.5 as compared to the cultivar "Flor de Mayo Bajío" with a harvest index of about 0.6 and a grain yield which is 25 % higher than of "Flor de Mayo Bajío". Determination of harvest index in an advanced stage of progeny selection would help in the breeding of such genotypes.

N balances for common bean and field pea. When the amounts of fixed N and grain N are known, the potential of a grain legume crop to increase soil N can be calculated by difference (N-balance) and indicate whether the crop may contribute to or diminish the soil N pool. Nitrogen balances for common bean and field pea may vary significantly as indicated in Figure 2. The outcome of the balance strongly depends on the grain yield. When grain yields are low, e.g due to unfavorable conditions during grain filling and harvest, the translocation of N from vegetative plant parts to grain may be hampered resulting in high amounts of N present in the crop residues. In a comprehensive study, Evans *et al.* (1989) found that the N balance for pea may vary between -32 and 96 kg N ha^{-1}, indicating that the value of a pea crop in terms of contributing to the N-sustainability of agroecosystems differ tremendously. Peoples and Craswell (1992) also reported that N-balances for tropical grain legumes may vary from -74 to + 136 kg N ha^{-1}. Although grain legume crops may have a negative N balance and thus indicate that the crop is not N sustainable, grain legumes normally have more positive N-balances than cereals, especially

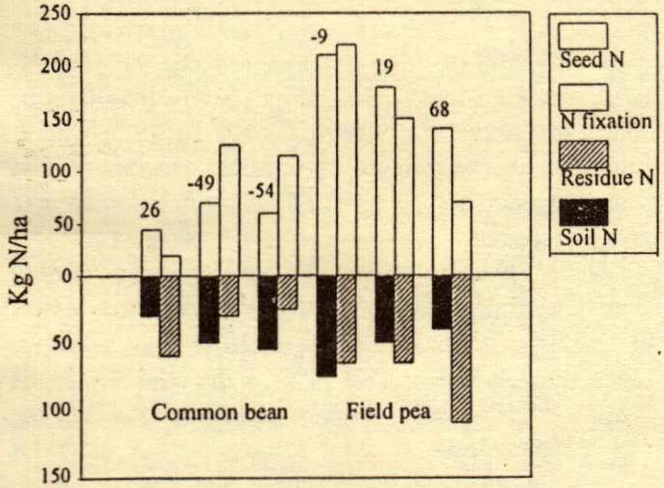

Figure 2. Nitrogen balances for common bean and field pea. Ref.: Common bean (Kucey, 1989; Peña-Cabriales *et al.*, 1993; Ruschel *et al.*, 1982. Field pea (Evans *et al.*, 1989; Jensen, 1989; Rennie and Dubetz, 1986). Numbers on top of the columns are the calculated net N-balances.

Table 4. Nitrogen balance (kg N ha^{-1}) for field pea and spring barley grown in pure stands or in a 1:1 mixed intercrop. Crops were fertilized with 50 kg N ha^{-1} labelled with ^{15}N (Jensen *et al.*, 1985).

Parameter	Pure stand pea	Intercrop† pea	Intercrop† barley	Pure stand barley
Total N	271	52	106	112
N_2-fixation	165	43	-	-
Fert. N in crop	31	2	30	33
Soil N in crop	75	7	76	79
Seed N harvested	201	45	77	88
Crop residue N	70	7	29	24
N balance	-5	0	-47	-55

† Intercrop plant population: 50 % of each pure stqand plant population.

when cereals are grown at low N levels (Table 4). In intercrops of grain legumes and cereals the N-balance will be determined by the dominant intercrop species. In a pea-barley intercrop, barley is the dominant species and the N-balance of the intercrop will approach the barley crop N-balance (Table 4). Since the proportion of total N in crop residues was higher in intercropped than pure stand barley, the intercrop N-balance was less negative than for barley grown in pure stand.

Effect of grain legume N-sparing on associated and subsequent crops. A grain legume crop may influence the N-nutrition of associated and subsequent crops via the "N-sparing" effect and the amount and mineralization rate of legume crop residues. In the intercrop situation an associated cereal may take up much more soil N per plant than in pure stand cereal, due to the N-sparing effect (or low competitive ability for soil N) of the grain legume (Table 4). Since the grain legume can fix its own N, the N-sparing effect of a grain legume in intercrop will result in a better resource use.

After cultivating grain legumes, the mineral soil N left may contribute to the N-nutrition of subsequent crop. In a temperate soil autumn sown crops took up on average 77 and 44 kg N ha^{-1} after pea and oats, respectively, during the autumn and winter period (Jensen and Haahr, 1990). Similarly, Senaratne and Hardarson (1988) found that sorghum succeeding field pea and spring barley took up 75 and 34 kg N ha^{-1}, respectively. Evans *et al.* (1991) used multiple regression techniques to separate the effect of N spared after a legume crop and N in legume residues on succeeding wheat. They found that about 80 % of the difference in soil inorganic N present in the soil after harvest of a grain legume and a cereal crop was recovered in the succeeding wheat.

It is well known that crop rotation increases yield over monocrop yield and this "break-crop" effect may not be compensated for by N-fertilization (Bullock, 1992). The causes for the rotation effects are not well understood but improvement in soil physical properties and reduction of soilborne pathogens may be responsible for yield increases besides the N benefits (Bullock, 1992; Evans *et al.*, 1991; Jensen and Haahr, 1990).

Contribution of grain legume crop residue N to associated and subsequent crops. The decomposition and net mineralization of N from grain legume residues may proceed rather fast due to the narrow C/N ratio of the residues. However, among several factors, the lignin and polyphenol contents of the residue may significantly influence the residue N mineralization rate (Fox *et al.*, 1990).

Nitrogen deposited in the rhizosphere may be taken up by an associated plant in the intercrop situation. Such transfer of legume N to associated cereals is rather small; <5 % of grain legume N transferred (Jensen, unpublished results). However, under conditions of severe N-limitation the N transferred from pea to barley may exceed 10 % of the N in the barley plants (Jensen, unpublished results).

Jensen (1994a) found that about 25 % of the N in mature pea crop residues (straw, empty pods and roots) was apparently mineralized within 10 days of decomposition in the field. This highlights the importance of planting a crop as soon as the grain legume is harvested in order to recover N spared and residue N mineralized. Winterbarley established at the time of pea residue incorporation recovered 13 % of the residue N during the three months following incorporation (Jensen, 1994b). At maturity the recovery was only slightly increased to 15 % (Table 5; Jensen, 1994b). The recovery of grain legume residue N in a subsequent crop may vary from less than 10 % to higher than 30 % (Table 5) depending on the climatic conditions, the residue N-mineralization rate, and the cropping system. Similarly, the relative contribution of residue N to the N-nutrition of the subsequent crop varies and depends on the amount of reside N incorporated and mineralized and the amount of fertilizer N applied (Table 5).

The N contribution from grain legume residues to a subsequent crop is derived from both N_2-fixation and soil N uptake in the legume crop (Heichel, 1987). Another important aspect is that the incorporation of grain legume residues may influence the turnover of soil organic N (Yaacob and Blair, 1980).

Consequently, the net effect of residue N may be positive or negative in terms of soil N uptake in the subsequent crop, and the uptake of residue N may be counterbalanced by a lower uptake of soil N compared to the N uptake in a crop grown on soil without residue incorporation. Jensen (1994b) found that the increased N uptake in winterbarley, due to incorporation of pea residue was equal to the amount of residue N taken up, indicating no significant "added nitrogen interaction" due to pea residue incorporation.

During the first year of decomposition, the major part residue N may be mineralized, e.g. c. 50 % of the pea residue N (Jensen, 1994a). In the following years the mineralization of residue N is much slower indicating that the residue derived N remaining are now a part of the stabilized soil organic N pool (Jensen, 1994a). Consequently, the recovery of pea residue N in the second and third subsequent crops after pea were only 3 % and 2 %, respectively (Jensen, 1994b). This is in agreement with results reported for other legume materials e.g. Heichel (1987) and Ta and Faris (1990).

Grain Legume Cultivation and Environmental Quality

Cultivation of grain legumes reduces the need N-fertilizers. Non-renewable energy sources may thus be conserved since less N-fertilizer has to be produced. Environmental effects of N-fertilizer production and transport, such as CO_2 (green-house gas) emission may thus be reduced.

Under climatic conditions where heavy rainfall shortly after application of the fertilizer N may result in leaching, grain legume N_2-fixation may result in reduced leaching losses of N. On the other hand, the N-spared during cultivation of grain legumes and the fast mineralization of grain legume residue increases the risk of losing N by leaching and denitrification. Only limited data are available on the leaching of N during cultivation of grain legumes. Kjellerup (1991) reported that the leaching of nitrate in lysimeters was twice as high after field pea as compared to spring

Table 5. Recovery of grain legume residue N in a subsequent crop. Data are derived from ^{15}N experiments.

Grain legume	Subsequent crop	Residue N	Residue N recovered	N in crop derived from residues	Reference
		kg N ha^{-1}	%	%	
Soybean	Cowpea	29	9	3	Sisworo *et al.*, 1990
Soybean	Maize	16†	18-33	11-12	Hesterman *et al.*, 1987
Soybean	Oats	215	6	29	Bergersen *et al.*, 1992
Pea	Sorghum	34	26	13	Senaratne and Hardarson, 1988
Pea	W. barley	83	15	5	Jensen, 1994b
Fababean	Sorghum	88	7	9	Senaratne and Hardarson, 1988
Fababean	S. barley	73	17	19	Müller and Sundman, 1988

† Only fixed N_2 from residues.

barley, and winterbarley succeeding pea reduced the N-leaching with only 10 to 16 %. Huber *et al.* (1987) found that the leaching of N during cultivation of fababean succeeded by winterwheat was about 20 kg N ha^{-1} higher than from corn for silage succeeded by winterwheat. Experiments with ^{15}N-labelled pea residues (2.2 % N) have shown that only 7 to 16 % of the residue N may be leached as nitrate from a temperate uncropped soil during the first leaching period (Jensen, 1994c). One experiment showed that incorporating the pea residues significantly reduced the total leaching as compared to soil without residues incorporated (Jensen, 1994c). It was suggested that this was due to increased microbial activity and thus a higher temporarily immobilization of soil N and/or increased denitrification due to the residue C added being a substrate for the denitrifying microbial population in a soil with a high level of nitrate (Aulakh *et al.*, 1991; Jensen, 1994c).

Aulakh *et al.* (1991) found that incorporated soybean residues increased the denitrification rate compared to wheat residue amended and unamended control soils during early stages of decomposition. The total denitrification from soybean and corn residue amended soil (residues had similar C/N ratios) was similar, but the $N_20/(N_2+N_20)$ ratio was higher in the soybean residue amended soil. Increased losses of N by denitrification, and production of N_20 (a green-house gas), due to grain legume residue incorporation is not in harmony with the resource and environmental aspects of the sustainability issue. However, more research is needed on leaching and denitrification losses due to grain legume cultivation.

Managing Grain Legume Cultivation in Low Input Sustainable Agriculture

Grain legumes should be managed to maximize symbiotic N_2-fixation, spare soil N for inter- or subsequent crops and enrich the soil with N. The potential saving of N-fertilizer cost could then enable the farmer to purchase phosphorus and other fertilizers needed to improve soil fertility.

Important management methods to maximize N_2-fixation have been indicated above. Two essentials are (1) inoculation with *Rhizobium*, if soils are devoid of efficient native strains and (2) the maintenance of soil fertility in terms of other nutrients than N. Alleviating water stresses seems also to be an important factor in obtaining high rates of N_2-fixation (Jensen, 1987; Peña-Cabriales and Castellanos, 1993). Management methods to increase the proportion of N in the plant derived from N_2-fixation is to intercrop with a cereal, but due to competition for other growth factors than N, fixation per plant may be reduced compared to pure stand legumes. By intercropping soil N may be used more efficiently than by pure stand cultivation of grain legumes and the risk of spared N being leached after harvest is reduced. Incorporation of crop residues with a wide C/N ratio to immobilize N prior to grain legume cultivation is also a potential method to increase the proportion of N_2-fixation in legumes, but there is a risk that other nutrients, e.g. P, may also be temporarily immobilized in the microbial biomass. The problem of an open N cycle after cultivation of grain legumes may be reduced by N-catch cropping either by undersowing the grain legumes with the catch crop or by establishment of a fast-growing non-legume with a high capacity for N uptake at harvest (Jensen, 1991). Finally, grain legume residues are an important factor in managing soil mineral N levels after grain legume cultivation. Incorporation of crop residues with a wide C/N, e.g. wheat straw, may immobilize spared N after a grain legume crop and reduce leaching losses of N.

CONCLUSIONS

Grain legumes are an important component of a low input, sustainable agroecosystem due to their ability to contribute protein and N to the agroecosystem, where other N inputs are small. However, the N sustainability of grain legumes at the field scale depend on their soil N use and the proportion of total crop N returned to the soil in residues. Grain legumes may deplete soil N sources, due to the fact that the main part of N is present in the grain, which is harvested, although the depletion rate may be much slower than of a cereal grown without N-fertilization. Cultivating grain legumes reduces the need for N-fertilization and thus conserves non-renewable energy sources, which should otherwise have been used for producing, transporting and applying N-fertilizers. In order to optimize the conservation of the N fixed by grain legumes, which is not removed with the harvested grain, it is important to improve management methods to reduce losses of N by leaching and denitrification during and after cultivation of grain legumes.

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SOIL DENITRIFICATION AS INFLUENCED BY CONSERVATION MANAGEMENT PRACTICES

Efecto de las Prácticas de Conservación sobre la Desnitrificación del Suelo

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SUMMARY

Alternative management systems using legume cover crops to reduce chemical N inputs and reduced-tillage management to control erosion and weeds conserve soil resources and environmental quality but can alter N cycling and availability to grain crops. This on-farm research was initiated in central Iowa to compare corn (*Zea mays* L.) yields and N availability for ridge-tillage with a legume winter cover crop (RT+CC) and conventional disk tillage without a cover crop (CT-CC) management systems. Although several components were evaluated, this report focuses on soil denitrification losses from the two management systems. Soil denitrification was assessed in the laboratory using acetylene-inhibition on intact soil cores that were taken from the field at several times during two growing seasons. Soil respiration, water content, bulk density, water-filled pore space (WFPS), and nitrate content were also measured. Soil denitrification losses for the RT+CC system were 3 to 16 times greater than those from the CT-CC system during the early to mid growing season. Losses from the RT+CC system ranged from 40 to 260 g N ha^{-1} d^{-1} and occurred mainly in the wetter, more compact, wheel-track interrows where crop residues were concentrated. Pre-planting cultivation between rows in a RT study reduced early season denitrification losses by two-fold, from 141 to 72 and from 174 to 90 g N ha^{-1} d^{-1}. We conclude that surface soil denitrification losses were primarily influenced by soil physical conditions (mainly WFPS), C availability, and soil nitrate levels as determined by tillage and crop residue management practices. The results illustrate the importance of management-induced temporal and special variation in the soil environment and their effect on N cycling, crop productivity, and environment quality.

Index words: *Ridge-tillage, conventional tillage, legume cover crops.*

RESUMEN

Los sistemas alternativas de manejo, utilizando cultivos de cobertera con leguminosas, para reducir insumos químicos de nitrógeno y manejo de labranza reducida para controlar la erosión y las malezas conservan los recursos del suelo y la calidad ambiental pero pueden alterar el ciclo del nitrógeno y su disponibilidad para los cultivos de grano. Esta investigación en terrenos de agricultores se inició en la región central de Iowa y tuvo por objeto comparar los rendimientos de maíz y la disponibilidad de nitrógeno en el sistema de labranza en surco con cultivos de cobertura de leguminosa de invierno (RT+CC) y labranza convencional de discos sin cultivos de cobertera (CT-CC). Aunque se evaluaron varios componentes, este reporte se enfoca solamente sobre las pérdidas por desnitrificación en el suelo en dos sistemas de manejo. La desnitrificación del suelo fue evaluada en el laboratorio usando muestras inalteradas de suelo mediante la técnica de inhibición de acetileno. Estas muestras fueron tomadas del campo durante varias fechas de muestreo en la estación de crecimiento. Se tomaron datos de respiración del suelo, contenido de humedad, densidad aparente, espacio poroso ocupado por agua y contenido de nitratos. Las pérdidas por desnitrificación del suelo para la RT+CC fueron tres a 16 veces más grandes que para la CT-CC durante las etapas iniciales y en las etapas intermedias del desarrollo las pérdidas de los sistemas RT+CC variaron de 40 a 260 g de nitrógeno ha^{-1} dia^{-1} y ocurrieron principalmente en los surcos más húmedos

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y más compactos por donde pasaba la llanta del tractor y donde se concentraban los residuos de cultivo. El cultivo en pre-plantación entre los surcos, en un estudio bajo labranza reducida, redujo la desnitrificación en etapas tempranas hasta en dos veces: de 141 hasta 72 y de 174 a 90 g de nitrógeno ha^{-1} dia^{-1}. Concluimos que las pérdidas por desnitrificación superficial del suelo fueron primeramente influenciadas por las propiedades físicas del suelo, principalmente (WFPS), la disponibilidad de carbono y los niveles de nitrato en el suelo determinados para labranza y las prácticas de manejo de residuo. Los resultados ilustran la importancia del manejo de la variabilidad espacial en el medio ambiente del suelo, del ciclaje de nitrógeno, de la productividad del cultivo y de la calidad ambiental.

Palabras clave: *Labranza en surco, labranza convencional, cultivos de cobertera con leguminosas.*

INTRODUCTION

In many parts of the world, agriculture struggles to increase food production to meet the food and fiber needs of rapidly growing populations. Intensive cultivation and monoculture production of cereal grain crops, development of higher yielding varieties, and greater use of synthetic inorganic fertilizers and other inputs have increased crop yields two to five fold during the last five decades in developed and developing countries. These yield increases, however, have sometimes been associated with declines in soil productivity due to soil erosion and loss of organic matter. Increased purchase of off-farm inputs has also been associated with decreased profitability due to rising costs and falling prices for grain. Ground and surface water contamination and environmental pollution have increased due to runoff, leaching, and gaseous losses of N from soil (Aulakh *et al.*, 1992). These consequences of management, coupled with climatic uncertainty and potential for drought, threaten the sustainability of agriculture and challenge farmers and researchers to develop agricultural production systems that will reduce soil erosion, loss of N and other nutrients to water and the atmosphere, and efficiently conserve and utilize rain and snowmelt water.

No-till and reduced-tillage farming systems which maintain crop residues on the soil surface can significantly reduce wind and water erosion and efficiently conserve soil-water. However, no-and reduced-till soils are often cooler, wetter, and more compact than conventionally-tilled soils (Aulakh and Rennie, 1986; Mielke *et al.*, 1986) resulting in greater potential for a less aerobic microbial environment (Doran and Linn, 1994; Linn and Doran, 1984), greater N losses through denitrification (Aulakh *et al.*, 1984; Fox and Bandel, 1986; Rice and Smith, 1982), lower net mineralization of N (Doran, 1987; Carter and Rennie, 1982) and, in some instances, lower crop yields. Use of winter legume cover crops in conservation tillage systems can improve N-use efficiency by providing biologically fixed N, reducing potential for N leaching losses, and improving soil productivity by reducing erosion (Doran and Smith, 1991; Power, 1987). Consequently, research efforts to find suitable alternative management systems using legume cover crops have recently increased (Doran *et al.*, 1987; Francis *et al.*, 1990; NRC, 1989).

Information on N mineralization-immobilization turnover, N leaching and denitrification losses, and crop yield potentials is needed to evaluate the economic viability and sustainability of any agricultural production system. To address these information needs, a field experiment was initiated in 1988 by Richard Thompson, a farmer, near Boone, Iowa. Tillage management comparisons included (a) ridge tillage with a hairy vetch winter cover crop (RT-CC), and (b) conventional tillage with no cover crop (CT-CC). Earlier findings (Doran, 1990; Doran *et al.*, 1989; Karlen and Doran, 1991) revealed lower early season available N in RT+CC systems. This resulted in part from denitrification losses and apparently limited plant growth and grain production as compared with CT-CC. In 1990, a pre-planting cultivation treatment was evaluated in RT as a practice that would reduce denitrification losses and enhance mineralization of organic N. The objective of the research reported here was to estimate the losses of N through denitrification as effected by tillage, residue management, and use of a winter legume cover crop.

MATERIALS AND METHODS

The experimental site, located on the Richard and Sharon Thompson farm near Boone in Central Iowa, is characterized by a humid continental climate with a mean annual precipitation of 848 mm. The site (field 4) has 0-2 % slope and the soil at the experimental site is a Nicollett loam (fine-loamy, mixed, mesic Aquic Hapludoll). The surface soil (0-30 cm) has 23 % sand, 38 % silt, and 39 % clay, a 1:1 soil:water pH of 6.5, and organic C and total N contents of 29.5 and 2.4 g kg^{-1}, respectively. The experimental area has been cropped to a corn-soybean (*Glycine max* L. Merr.) rotation, without application of animal manure, since 1983. A denitrification study was conducted in two field experiments during April to November in 1989 and 1990. The treatments selected for this study were as follows:

1) In 1989, a tillage and cover crop experiment was initiated in field 4B in an area previously established in a corn-soybean rotation. A cover crop mixture of oats (*Avena sativa* L.), rye (*Secale cereale* L.), and hairy vetch (*Vicia villosa* L. Roth) was seeded on 17 September 1988 at rates of 10, 8, and 15 kg ha^{-1}, respectively. Corn (*Zea mays* L.) was planted on May 6, 1989 with a Flieshman Buffalo ridgetill-planter at a rate of 66,200 seeds ha^{-1} in rows 90-cm apart with a band application of 83 kg K ha^{-1}. Ammonium nitrate (NH_4N0_3) fertilizer was surface applied as a liquid on May 29 and incorporated into soil with 4.6 mm of water. Two rotary hoeings and two cultivations were done on 1 to 2 week intervals after planting for weed control.

a) Conventional-tillage without a cover crop (CT-CC): Crop residues from soybean were incorporated in soil by disking in October 1988 and again in late April and early May, 1989, prior to planting corn. The fall disking prevented establishment of the cover crop seeded to this area.

b) Ridge-tillage with winter cover crop (RT+CC): As described earlier, a mixture of hairy vetch, rye, and oat was overseeded into the soybean crop before harvest in September 1988. Winter cover crops and soybean residues were maintained until corn was planted in May 1989. Soil and crop residues were moved out of the ridge of the previous crop with a Buffalo ridge-till planter. This controls weeds in the row, creates a warmer seedbed environment, and enhances mineralization of organic N. Subsequent rotary hoeing and cultivation operations, the same as for CT-CC, further enhanced weed control and N mineralization from crop residues. No herbicides were used to control weeds.

2) Pre-plant soil cultivation in RT+CC: In spring 1990, RT plots were divided into two halves to evaluate the effectiveness of pre-plant cultivation. Pre-plant cultivation was done on 20 April 1990 in the between-row (interrow) areas using flat, 61-cm wide-sweeps. Corn was seeded on 7 May 1990 and 39.2 kg N ha^{-1} was applied as starter fertilizer sidedress applications at planting, 10.1 kg N ha^{-1} as liquid starter (5-12-11) and 29.1 kg N ha^{-1} as dry starter (15-10-33). As in the previous year, two rotary hoeings (May 16 and June 4) and two cultivations were performed during the crop growing season. Use of four-row equipment resulted in alternate between row (interrow) areas being trafficked wheel tracks.

Gaseous N losses via denitrification were measured following the acetylene-inhibition soil core method (Aulakh *et al.*, 1982). Four replicate areas were selected for each treatment and three locations (row, interrow non wheel track, and interrow wheel track) were selected for this study. Undisturbed soil cores (6.6-cm diam. by 7.5-cm deep) from each location were taken by driving stainless steel cans into the soil with a hand-operated slide hammer. Each soil core was then immediately removed, enclosed in a plastic bag, and placed in a cooler. After returning to the laboratory, each core was placed in a 1.9 L jar and sealed with screw-lids that had a serum stopper fitted for gas sampling. In each jar, 10 % of headspace was replaced by acetylene (C_2H_2) that was pre-scrubbed through 6M H_2S0_4 and H_20 to remove acetone. After 24 h incubation at 25 °C, two 1-cm^3 gas samples of headspace atmosphere from each jar were taken for N_20 an $C0_2$ analysis by gas chromatography (Aulakh *et al.*, 1991). The jars were opened and soil-cores weighed. Acetylene-saturated water (2 to 3 cm) was applied to the surface of each core to ensure immediate blockage of N_20 reduction and to simulate rainfall, and cores were replaced in jars. Acetylene (10 % vol/vol) was then added to each incubation jar, and the jars were resealed. After 24 h incubation at 25 °C, gas samples were taken from each jar, the cores were weighed, and then oven-dried at 105 °C for 3 d. Soil water content, water-filled pore space (WFPS), and bulk density were calculated from the volume and weight of each individual core. The data were corrected for the solubility of N_2O and CO_2 in soil water as described by Moraghan and Buresh (1977). During 1990, a second set of soil samples were collected along with soil-cores. Soil NO_3- and NH_4-N were measured by extracting representative 10 g sub-samples with 1M KCl (30 min shaking) followed by automated colorimetric analysis of filtered extracts (Keeney and Nelson, 1982).

In 1989, comparisons between tillage management systems were made using adjacent 8-row strips with four replications (field 4B). Consequently, statistical analyses were limited to using a paired t-test for mean comparisons. In 1990, the pre-cultivation experiment with RT management was conducted in the same field, 0.4 km north of the 1989 study (field 4D). The experimental design for the 1990 study was a randomized complete block arranged in a split plot design with four replications. Pre-plant cultivation treatment represented the main plot. Statistical analyses were performed using the SAS general linear models procedure (SAS Institute, 1982).

RESULTS AND DISCUSSION

Soil nitrate levels in the surface 30 cm of the RT-CC system averaged 25 to 42 kg N ha^{-1} lower than the CT-CC system before planting and during the early growing season in 1989 (Table 1). The soil nitrate content for the surface 30 cm of the RT+CC system on June 20 was 52.8 kg N ha^{-1}, 25 kg N ha^{-1} below the 78 kg N ha^{-1} estimated (21 ppm) to be needed at this stage of growth for optimum grain yield of corn in this region (Blackmer *et al.*, 1992). For the same date, soil nitrate levels for the CT-CC system appeared adequate for corn production. The difference in soil nitrate levels between management treatments was greatest in the crop interrow areas where differences in soil density, residue cover, soil water content, and temperature were also greatest.

The manager using RT and winter cover crops to produce corn is challenged by need to minimize soil nitrate levels during the non-growing season to reduce potential N leaching loss, but must also assure that

Table 1. Soil nitrate levels during the 1989 growing season for three depth increments in surface soil (0-30) for row and interrow locations † under conventional tillage without cover crops and ridge tillage management with cover crops.

Location	Soil nitrate-N levels (kg N ha^{-1}) at respective sampling depths (cm)							
	Conventional tillage				Ridge tillage + cover crop			
	0-7.5	7.5-15	15-30	0-30	0-7.5	7.5-15	15-30	0-30
	before planting corn (April 24)							
Row	4.1	5.0	7.4	16.5	4.6	3.1	6.0	23.7
Interrow	8.3	9.9	14.9	33.1	2.9	2.3	5.1	10.3
Total †				49.6*				24.0
	after planting corn (May 15)							
Row	7.3	6.2	7.8	21.3	2.6	1.1	2.0	5.7
Interrow	15.5	13.9	16.3	45.6	11.6	3.7	4.2	19.5
Total				66.9*				25.1
	early season (June 20)							
Row	17.9	4.4	9.2	31.5	14.9	3.0	4.8	22.7
Interrow	20.1	10.8	14.7	45.6	16.7	6.3	7.1	30.1
Total				77.1*				52.8
	mid season (July 25)							
Row	9.5	1.7	1.5	12.7	8.2	1.1	1.4	10.7
Interrow	4.2	1.8	2.7	8.7	4.0	1.9	2.3	8.2
Total				21.4				18.9
	post harvest (October 3)							
Row	2.7	1.9	1.8	6.4	4.4	2.3	1.7	8.4
Interrow	3.8	2.5	3.1	9.4	4.3	2.1	2.7	9.1
Total				15.8				17.5

† Each sample was a composite of sixteen 19.4 mm diameter soil cores from row and interrow areas. Row area defined as 15 cm to either side of the crop row.

‡ Relative area under row and interrow areas represented 33 % and 67 %, respectively, of the total surface area.

* Total values for 0-30 cm depths between treatments within each date differ significantly at P>0.05.

Table 2. Denitrification losses (N_2O-N), water-filled pore space (WFPS), and respiration (CO_2-C) in surface soil (0-7.5 cm) of row, interrow nonwheel track (NWT) and interrow wheel track (WT) areas † under conventional tillage (CT) and ridge tillage (RT) management with cover crops before and after irrigation with 29.2 mm of water.

Management system	Parameter	Pre-irrigation				Post-irrigation			
		Row	Interrow NWT	Interrow WT	Total/ average‡	Row	Interrow NWT	Interrow WT	Total/ average
		Before planting corn (April 24, 1989)							
CT	N_2O-N (g ha^{-1} d^{-1})	-	-	-	-	0.6	0.6	1.4	2.6
RT	"	-	-	-	-	2.2	8.9	29.4	40.5*
CT	WFPS (%)	-	-	-	-	48.7	48.7	48.3	48.6
RT	"	-	-	-	-	50.3	63.4	77.8	63.8*
CT	CO_2-C (kg ha^{-1} d^{-1})	-	-	-	-	0.6	0.6	1.6	2.8
RT	"	-	-	-	-	1.2	1.4	0.8	3.4
		After planting corn (May 15, 1989)							
CT	N_2O-N (g ha^{-1} d^{-1})	21	25	42	88	554	159	356	1069
RT	"	4.5	114	142	260*	160	290	551	1001
CT	WFPS (%)	25.1	38.6	40.5	38.1	95.2	92.2	104	97.1
RT	"	32.6	44.3	42.7	39.9	95.2	86.3	93.3	91.6
CT	CO_2-C (kg ha^{-1} d^{-1})	5.4	8.9	4.8	19.1	-	-	-	-
RT	"	2.9	40.9	99.6	143*	-	-	-	-
		After harvesting corn (October 26, 1989)							
CT	N_2O-N (g ha^{-1} d^{-1})	7.6	140	44	192*	71	96	71	238
RT	"	8.3	39	51	98	116	17	54	187
CT	WFPS (%)	44.6	78.6	67.2	63.5*	69.7	97.3	91.2	86.1
RT	"	42.0	65.3	63.4	56.9	66.5	83.0	84.6	78.0
CT	CO_2-C (kg ha^{-1} d^{-1})	5.0	7.2	5.3	17.5	6.3	0.8	1.1	8.2
RT	"	7.0	9.2	9.5	25.7*	8.9	4.5	6.4	19.8

† Relative area under each row, interrow nonwheel track and interrow wheel track represented 33 % of the total surface area except on April 24, when there was no distinguishable row area in CT plots.

‡ Total of N_2O-N and CO_2-C but average of WFPS.

* Values between treatments for pre-irrigated and post-irrigated within each date differ significantly at P>0.05 for respiration and WFPS and P>0.10 for denitrification.

sufficient available N is present during the growing season to produce an adequate corn crop. In 1989, the final grain yield of corn for the RT+CC system with a winter cover crop was 8910 kg ha^{-1}, 10 % lower than that for the CT-CC system (9850 kg ha^{-1}).

Total denitrification losses from surface soil with RT management averaged 40 g N ha^{-1} d^{-1} in early spring before corn planting. This was 16 times greater than losses from CT soils, which averaged only 2.6 g N ha^{-1} d^{-1} (Table 2). The greatest denitrification losses, especially with RT, occurred from the interrow wheel-track areas where soil densities and water contents were greatest, crop residues were most concentrated, and soil nitrate contents were greatest for CT but lowest for RT (Table 1). Significant denitrification losses from soil generally occur when soil WFPS exceeds 70 % (Doran *et al.*, 1990). Soil respiration rates were low and did not differ significantly between treatments. It should be pointed out, however, that denitrification and respiration estimates made after irrigation, where WFPS exceeded 75 %, are likely conservative due to restricted diffusion of gaseous products out of the soil.

Estimated total denitrification losses from surface soil with RT management averaged 260 g N ha^{-1} d^{-1} one week after planting (May 15). This was three times greater than losses from CT soils which averaged 88 g N ha^{-1} d^{-1} (Table 2). As observed earlier in the season, denitrification losses were generally highest from interrow areas and lowest in the row. However, unlike earlier observations, the highest rates of denitrification occurred at WFPS values below 45 %. It is important to note that during the planting operation soil from the row is moved into the interrow and, the RT+CC system, is mixed with fresh and decomposing crop residues. This operation not only eliminates differences in soil density between management practices (Table 3) but also stimulates microbial activity which can result in significant denitrification under drier conditions if oxygen uptake by microorganisms exceeds the

Table 3. Potential denitrification (N_20-N), water-filled pore space (WFPS), respiration ($C0_2$-C), and soil bulk density on May 15, 1989 for three depth increments (cm) ofrow, interrow nonwheel track (I-NWT) and interrow wheel track (I-WT) areas† under conventional tillage (CT) and ridge tillage (RT) management before and after irrigation with 29.2, 5.8, and 4.4 mm of water.

Location in plot	Conventional tillage				Ridge tillage + cover crop			
	0-7.5	7.5-15	18.5-30	0-30‡	0-7.5	7.5-15	18.5-26	0-30‡
	Before Irrigation							
	Potential denitrification, g N ha^{-1} d^{-1}							
Row	20	145	80	325	4	22	14	54
I-NWT	25	120	100	345	113	29	17	176
I-WT	41	178	88	395	141	13	16	187
Total	86	443	268	1065*	258	64	47	417
	WFPS,%							
Row	35	61	66	54	33	56	60	50
I-NWT	39	62	65	55	44	60	61	55
I-WT	40	65	67	57	43	52	61	52
Average	38	63	66	55	40	56	61	52
	Respiration, kg C ha^{-1} d^{-1}							
Row	5.4	3.2	0.8	10.2	2.9	21.9	1.4	27.2
I-NWT	8.9	11.1	2.1	24.2	99.6	6.9	2.0	110.5
I-WT	4.8	6.3	0.9	12.9	41.0	5.1	1.8	49.8
Total	19.1	20.6	3.8	47.3	143.5	33.9	5.2	187.5*
	After Irrigation							
	Potential denitrification, g N ha^{-1} d^{-1}							
Row	549	100	66	791	158	36	19	233
I-NWT	158	145	79	461	288	62	34	418
I-WT	352	147	76	620	546	44	19	609
Total	1059	402	221	1902*	992	142	72	1260
	WFPS, %							
Row	95	75	77	82	95	70	71	79
I-NWT	92	75	76	81	86	74	72	77
I-WT	104	79	78	87	93	65	71	76
Average				83*				77
	Soil bulk density, g cm^3 (wet)							
Row	1.03	1.21	1.23	1.22	1.04	1.19	1.20	1.16
I-NWT	1.05	1.17	1.25	1.18	0.94	1.22	1.22	1.18
I-WT	1.16	1.24	1.25	1.22	1.02	1.17	1.23	1.16
Total				1.21				1.17

† Rates presented are weighted for row and interrow areas representing 33 % of the total surface area.

‡ Values for 18.5 -26 cm depth doubled for computation of 0-30 cm total.

* Treatment values for 0-30 cm depths within each date differ significantly at P>0.05.

diffusive capacity of the soil. This condition was indicated in our study where denitrification losses from the interrow areas with RT management on May 15 ranged from 114 to 142 g N ha^{-1} d^{-1} and WFPS was only 43-44 %. High levels of microbial activity, apparently stimulated by the recent incorporation of cover crop residues in the RT system, were reflected by correspondingly high rates of microbial respiration in the interrow areas. Aulakh *et al.* (1991) and McKenney *et al.* (1993) have demonstrated the effectiveness of hairy vetch residue in stimulating microbial activity and denitrification. Irrigation significantly increased denitrification from all management systems and row locations, especially for CT. After irrigation, when WFPS in all cases exceeded 86 %, no significant difference in denitrification was measured for the two management systems.

Greater denitrification losses from the CT system after corn harvest apparently occurred because of greater soil WFPS. There were no significant differences between systems after irrigation when WFPS exceeded 67 % in all cases. Slightly higher soil respiration rates from the RT+CC system at this time of year suggests greater availabilily of C to microorganisms than with the CT-CC system. Soil nitrate levels may have limited the total potential for denitrification with both management systems as they were very low after harvest (Table 1).

Table 4. Effect of pre-plant cultivation on denitrification losses (N_20-N), water filled pore space (WFPS), respiration ($C0_2$-C), Nitrate-N ($N0_3$-N) in row, and interrow nonwheel track (NWT) and wheel track (WT) areas † under ridge-till management in 1990. Treatments did not receive supplemental irrigation.

Parameter	No Pre-plant cultivation				Pre-plant cultivation			
	Row	Interrow NWT	Interrow WT	Total/ average‡	Row	Interrow NWT	Interrow WT	Total/ average
	Before planting corn (May 2, 1990)							
N_20-N (g ha^{-1} d^{-1})	15.0	36.3	89.3	141*	16.0	14.3	41.8	72.0
WFPS (%)	40.5	60.0	63.5	54.8*	40.5	46.0	54.0	46.8
$C0_2$.C (kg ha^{-1} d^{-1})	9.7	11.7	12.2	33.6	10.9	8.0	16.7	35.6
$N0_3$-N (kg ha^{-1} 7.5 cm)	11.2	8.5	9.8	9.8	14.7	7.8	13.4	12.0
	After planting corn (June 11, 1990)							
N_20-N (g ha^{-1} d^{-1})	9.0	79.0	85.7	174*	10.3	9.0	70.7	90.0
WFPS (%)	41.0	42.0	53.0	45.3	43.0	39.0	52.0	44.7
$C0_2$-C (kg ha^{-1} d^{-1})	3.0	13.9	14.2	31.5*	3.5	5.8	8.8	18.1
$N0_3$-N (kg ha^{-1} 7.5 cm)	51.6	20.2	13.8	28.5	69.0	19.1	13.5	33.9
	After tasseling of corn (July 16, 1990)							
N_20-N (g ha^{-1} d^{-1})	14.7	53.0	28.7	95	16.3	25.7	33.7	76.0
WFPS (%)	47.8	67.3	64.8	60.0	47.8	58.3	70.5	58.9
$C0_2$-C (kg ha^{-1} d^{-1})	6.4	5.0	4.2	15.6	7.7	4.1	4.0	15.8
$N0_3$-N (kg ha^{-1} 7.5 cm)	4.4	2.4	2.0	2.9	4.5	2.3	2.4	3.1
	After maturity of corn (August 27, 1990)							
N_20-N (g ha^{-1} d^{-1})	7.6	23.2	30.7	61.0	7.0	11.3	16.7	35.0
WFPS (%)	39.3	60.5	75.0	58.3	44.5	58.5	73.0	58.7
$C0_2$-C (kg ha^{-1} d^{-1})	5.7	3.7	3.9	13.3	6.1	3.1	3.2	12.4
$N0_3$-N (kg ha^{-1} 7.5 cm)	11.7	5.6	5.7	7.7	8.2	4.0	4.2	5.5

† Relative area under each row, interrow nonwheel track and interrow wheel track represented 33 % of the total surface area.
‡ Total of N_20-N, $C0_2$-C , and $N0_3$-N, but average of WFPS.
* Total/average values between cultivation treatments within dates differ significantly ($P > 0.05$).

During the 1989 growing season, measured and potential denitrification losses from surface soil were primarily influenced by soil physical conditions (mainly WFPS), C availability to microorganisms, and soil nitrate levels as affected by tillage and residue management practices. These results illustrate the importance of understanding the soil environment and its variations in time and space when evaluating the effects of tillage and crop residue management on N cycling processes, especially denitrification.

In our study, denitrification losses from management systems were mainly measured from surface soil but the need to also examine the effects of management on potential denitrification from deeper depths is illustrated by the data presented in Table 3. As discussed earlier, denitrification losses from the surface soil (0-7.5 cm) on May 15 were three-fold higher with RT than with CT management. However, the potential denitrification losses from deeper in soil reversed and were six to seven-fold higher for CT than RT management. This difference may have resulted, in part, from greater WFPS for CT management at this depth but also likely resulted from denitrification being limited in RT management by lower levels of available C and nitrate at these depths (Table 1). Denitrification assays conducted on cores extracted from various soil depths only represent potential for denitrification, but these results illustrate the need to exercise caution in using only surface cores for estimating the effects of management on denitrification losses.

In 1990, an experiment was initiated to evaluate the effectiveness of cultivating the between row areas with RT management before planting to reduce early season denitrification losses and to stimulate mineralization of N from the vetch cover crop. Unfortunately, the winter cover crop did not establish properly and vetch cover in spring of 1990 ranged from only 61 to 295 kg dry matter ha^{-1}. Surface residue cover from the previous soybean crop ranged from 107 to 291 kg dry matter ha^{-1}. The weather was extremely hot and windy during early spring of 1990, causing the soil to dry very rapidly following pre-plant cultivation. This reduced the effectiveness of cultivation in reducing denitrification and stimulating N mineralization. However, in spite of these obstacles, cultivation between crop rows before planting reduced

Table 5. Effect of pre-plant cultivation on denitrification losses (N_20-N), water filled pore space (WFPS), respiration ($C0_2$-C), and soil bulk density in row, and interrow nonwheel track (NWT) and wheel track (WT) areas † in surface soil (0-7.5 cm) under ridge-till management in 1990. Treatments received supplemental irrigation with 2 to 3 cm of water to simulate rainfall.

Parameter	No Pre-plant cultivation				Pre-plant cultivation			
	Row	Interrow NWT	Interrow WT	Total/ average‡	Row	Interrow NWT	Interrow WT	Total/ average
				Before planting corn (May 2, 1990)				
N_20-N (g ha^{-1} d^{-1})	386	631	1185	2202	118 63.5.	166	592	876
WFPS (%)	69.0	81.0	84.8	78.3*	9.9	70.3	76.5	70.1
$C0_2$-C (kg ha^{-1} d^{-1})	9.3	6.9	7.5	23.7	0.97	6.8	11.6	28.3
Soil bulk density (g cm^{-3})	0.98	1.25	1.27	1.17		1.05	1.13	1.05
				After planting corn (June 11, 1990)				
N_20-N (g ha^{-1} d^{-1})	515	1731	984	3230	585	986	825	2396
WFPS (%)	79.3	76.8	85.5	80.5	81.0	80.8	84.8	82.2
$C0_2$-C (kg ha^{-1} d^{-1})	1.0	4.7	1.3	7.0	1.1	3.1	1.2	5.4
Soil bulk density (g cm^{-3})	1.09	1.03	1.17	1.10	1.11	1.05	1.19	1.12
				After tasseling of corn (July 16, 1990)				
N_20-N (g ha^{-1} d^{-1})	274	195	104	573	347	85	130	562
WFPS (%)	70.8	83.5	77.8	77.4	70.8	77.8	82.8	77.0
$C0_2$-C (kg ha^{-1} d^{-1})	2.3	1.4	0.8	4.5	4.0	1.7	1.2	6.9
Soil bulk density (g cm^{-3})	1.02	1.25	1.31	1.19	1.00	1.21	1.35	1.19
				After maturity of corn (August 27, 1990)				
N_20-N (g ha^{-1} d^{-1})	183	87	223	493	239	86	234	559
WFPS (%)	61.3	84.3	88.5	78.0	67.3	78.0	92.0	79.1
$C0_2$-C (kg ha^{-1} d^{-1})	4.7	1.6	1.9	8.2	3.5	1.5	1.7	6.7
Soil bulk density (g cm^{-3})	0.93	1.19	1.38	1.17	1.01	1.21	1.35	1.19

† Relative area under each row, interrow nonwheel track and interrow wheel track represented 33 % of the total surface area.
‡ Total of N_20-N, $C0_2$-C, and $N0_3$-N, but average of WFPS and soil bulk density.
* Total/average values between cultivation treatments within dates differ significantly ($P > 0.05$).

early season denitrification losses by two-fold, with values ranging from 141 to 72 kg N ha^{-1} d^{-1} on May 2 and from 174 to 90 kg N ha^{-1} d^{-1} on June 11 (Table 4). Reduced denitrification losses with pre-plant cultivation apparently resulted from lower WFPS in interrow locations (Table 4), partly because of lower soil bulk densities (Table 5). The effectiveness of pre-plant cultivation in reducing denitrification loss for the June 11 sampling date was apparently not related to WFPS, as it did not differ between treatments. This was partially due to the planting operation which eliminated interrow differences in soil density for this date (Table 5). Increased microbial activity in the interrow of the non-cultivated treatment, as indicated by higher soil respiration, may have been the factor causing a higher denitrification rate for this treatment. Pre-plant cultivation had no effect on soil denitrification for July and August sampling dates.

In a wetter year, the effectiveness of pre-plant interrow cultivation with RT management in reducing denitrification losses would likely have even more pronounced than observed for the dry, 1990 season. This is illustrated by the data in Table 5, where, after irrigation with 2 to 3 cm of water to simulate rainfall, pre-plant cultivation resulted in significantly lower denitrification losses on May 2 before planting (from 2202 to 876 g N ha^{-1} d^{-1}). This effect primarily resulted from reduction of WFPS and soil bulk density in the interrow area with pre-plant cultivation.

CONCLUSIONS

During the early growing season the surface soil environment for ridge tillage management with legume containing winter cover crops was generally wetter, more compact, and more covered with crop residues than conventional tillage management without cover crops, particularly in wheel tracked between row areas. Under the soil and climatic conditions of our study, this resulted in greater denitrification losses and lower levels of plant available N in soil which partially resulted in 10 % lower corn grain yield with conservation management (9850 *versus* 8910 kg ha^{-1}). It is important to note, however, that yields of both management systems were excellent for rain-fed production in this area. Furthermore with conservation management, input costs are reduced by not applying herbicides and limiting fertilizer use to moderate amounts applied as a sidedress at planting or during cultivation. Although not considered in our study, the benefits of reduced soil erosion and N leaching losses with conservation management further enhance the benefits of these alternative production systems.

Between row cultivation with ridge tillage was an effective management tool in reducing early season denitrification losses of plant available N in soil. However, the potential added benefit of pre-plant cultivation on mineralization and release of N from crop residues was not observed in our study due to dry weather and failure of the winter cover crop to establish. An undesirable consequence of pre-plant cultivation was a 2 to 4 fold increase in broadleaf weed counts for ridge-tillage management without herbicides (Thompson, 1991). Consequently, despite the potential benefit to reducing denitrification losses and enhancing N mineralization, the practice of pre-plant cultivation with ridge-tillage management has been discontinued on this farm. This illustrates the importance of evaluating results of reductionistic, discipline oriented research within the broader context of a farming system which is facilitated by on-farm research.

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AGRICULTURAL SUSTAINABILITY AND SOIL NUTRIENT CYCLING, WITH EMPHASIS ON TROPICAL SOILS

Ciclaje de Nutrimentos y Sostenibilidad Agrícola en Suelos Tropicales

A. Van Diest[1]

SUMMARY

It is emphasized that the term "agricultural sustainability" has different meanings under different circumstances. In tropical farming systems, it is mainly low productivity that endangers the sustainability of agriculture. In the past, subsistence farming could stabilize a soil's productivity, but shortly after produce starts to be sold on markets the menace of soil degradation presents itself. Judicious recycling of nutrients in crop residues will not be enough to sustain the farming system. A plea is made to shift attention from low inputs of nutrients to low-cost inputs of nutrients, and to convert strictly arable farming systems into mixed systems. Together with crop residues, livestock can consume forage legumes, in which biologically fixed nitrogen and mobilized rock phosphates are present. The animal excreta should be collected in a biogas digester underneath a feedlot. Anaerobic fermentation, in addition to producing biogas, guarantees minimum losses of nutrients from excreta. The effluent, a liquid manure, can serve as principal source of nutrients, and contributes as well to soil organic matter conservation and buildup.

Index words: Phosphorus, potassium, agricultural subcycles.

RESUMEN

Se ha enfatizado que el término sostenibilidad agrícola tiene diferente significado bajo diferentes circunstancias. En sistemas agrícolas tropicales es principalmente la baja productividad la que pone en riesgo la sostenibilidad de la agricultura. En el pasado, los sistemas agrícolas de subsistencia podían sostener la productividad agrícola pero un poco después de que los productos se empezaron a vender en los mercados, empezó a ocurrir la degradación del suelo. El ciclaje juicioso de los nutrimentos en los residuos de cosecha no es suficiente para sostener los esquemas agrícolas. Consideramos que es importante un cambio de atención de la agricultura de bajos insumos de nutrimentos a bajo costo de los nutrimentos; y convertir sistemas de cultivo estricto a sistemas integrados. Juntamente con los desechos de cultivo, el ganado y el consumo de forrajes de leguminosas en las cuales el nitrógeno es fijado biológicamente y los fosfatos provenientes de roca fosfórica son movilizados. Los desechos animales deben ser colectados para la producción de biogas. La fermentación anaeróbica en adición a la producción de biogas garantiza un mínimo de pérdida de nutrimentos. El efluente puede servir como fuente principal de nutrimentos y contribuir al mismo tiempo a establecer y conservar los niveles de materia orgánica en el suelo.

Palabras clave: Fósforo, potasio, subciclos agrícolas.

INTRODUCTION

The fashionable term "agricultural sustainability", as it appears in the title of this paper, turns out to have different meanings to different people. As a result, if not at the start the term is properly defined, discussions on the sustainability of agriculture run the risk of ending up in confusion.

To give an example, in the so-called developed world the sustainability of agriculture is not in the first place endangered by shortages of resources or by deterioration of environmental quality, but by sanctions imposed upon violators of ecological directives regarding maximally permissible concentrations of nutrients and pesticide residues in the atmosphere, in surface water and in deep groundwater. It must be admitted that in my home country, the Netherlands, farmer's organizations and governmental authorities in the Department of Agriculture are partially to blame

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for the present difficult situation into which they are being maneuvered by environmentalists. Too long they have closed their eyes to excessive use of liquid manure and pesticides. The result is that unrealistic regulations imposed by national and supranational lawmakers will endanger the economic viability of farming and, thus, the sustainability of agriculture in the Netherlands and in other Western European countries.

The situation in tropical countries is often entirely different. Commonly low soil productivity, the term appearing in the title of this symposium, constitutes the main cause of endangered agricultural sustainability. A question that might come to mind at this stage is "what exactly does the term soil productivity stand for"? Textbooks on soils do not provide much help in answering this question. Of ten textbooks in either the English or the German languages that I consulted, only two gave an answer. One considered the term "soil productivity" synonymous with the term "soil fertility".

In my own teaching I have always attached a broader meaning to "soil productivity" than to "soil fertility". In this view the fertility of a soil expresses the relative capacity of that soil to provide nutrients to a crop, while "soil productivity" in addition expresses the capacity of the soil,

- to retain moisture and to provide it to a crop,
- to enable gas exchange to take place between atmosphere and soil, and
- to allow a root system to extend throughout that section of the soil in which available nutrients and moisture are present.

In the tropics, agricultural sustainability can be endangered by flaws in any one of these four soil characteristics or a combination of some of them. Low water holding capacity of sandy soils, and poor permeability of water and/or air of clay soils and soils with fragipans often endanger the sustainability of agriculture. A widespread menace is further the high acidity and ensuing Al toxicity of subsoils preventing roots from making use of valuable moisture and nutrients in the subsoil.

Nevertheless, inadequate nutrition is certainly the most prominent obstacle to agricultural sustainability in the tropics. For this reason, the remainder of this paper will deal with the relationships between nutrient cycling and agricultural sustainability under tropical conditions. For reasons of limited time and space the discussion must be confined to the nutrients nitrogen, phosphorus and potassium.

Nutrient Cycling

The present high interest in nutrients cycling is undoubtedly prompted by the desire of agricultural policymakers to stem the flow of nutrients to compartments of the environment into which an influx of nutrients is considered undesirable. The qualitative aspects of the various nutrient cycles have already been known for a long time, but much is still to be learned about quantities involved. For example, it is common knowledge that denitrification constitutes the concluding step in closing the nitrogen cycle, but comparatively little is known yet about the relative quantities of nitrogen gas (N_2) and nitrous oxide (N_20) escaping from the earth surface, and about the fate of the N_2O once it has entered the atmosphere.

Global nutrient cycles are often composed of a number of subcycles, one of which might be called the agricultural subcycle. An example is given for the nutrient potassium in Figure 1. In this subcycle, the nutrient is transferred from soil to crop and, ideally speaking, the portion of the nutrient present in the non-marketable parts of the crop is supposed to return to the soil and to remain there for uptake by the next crop. A loss of a part of the nutrient mass involved to the hydrosphere causes a pollution of the environment and, in addition, reduces the feeding power of the crop with respect to the subsequent crop.

Advocates of alternative agriculture are often unrealistic in their claims that conservation of nutrients present in such subcycles in tropical regions can eliminate the need of fertilizers. Very often such misconceptions stem from experiences in European and North American agriculture where long-term use of fertilizers and manure have resulted in reservoirs of soil nutrients that sometimes can be tapped for many years before serious yield declines set in. The exaggerated ideas advanced about nutrient cycling serving as a panacea to all nutritional problems are just as unrealistic as the names coined for these farming systems, such as "ecological agriculture" and "biological agriculture". These names raise the erroneous impression that agriculture in which chemicals, such as fertilizers and pesticides, are used would have lost touch with ecology and biology.

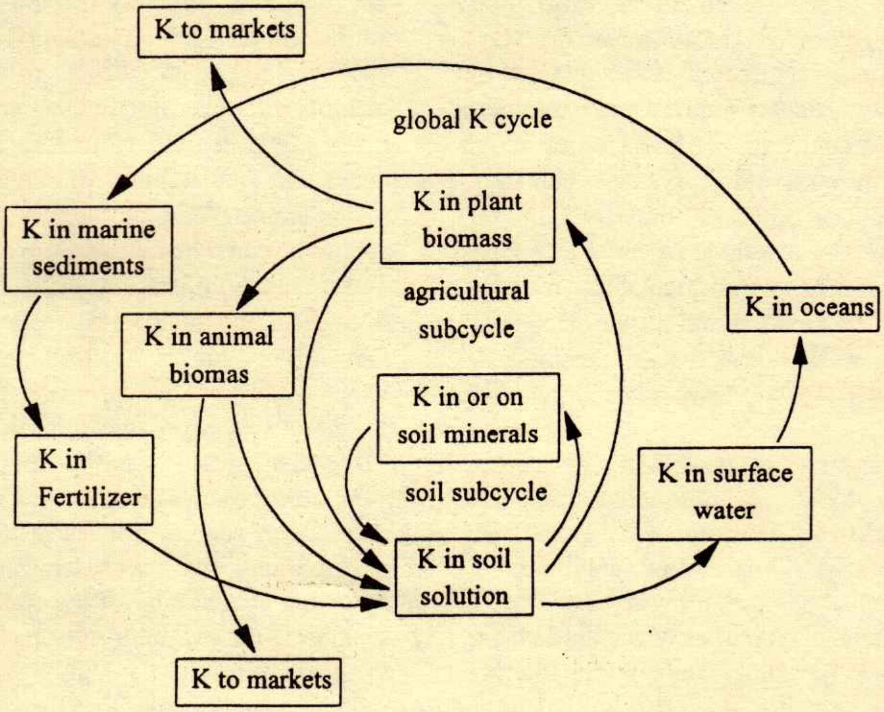

Figure 1. The global potassium cycle, within which two subcycles operate.

In its most ideal form, subsistence farming could be practiced for a long time without any soil depletion or soil deterioration, as long as care was taken to retain all nutrients in the farming ecosystem. However, soon after produce starts to be sold on a market, a judicious recycling of nutrients in an agricultural subcycle, however useful this may be, will prove to be inadequate to sustain the farming system. Most tropical soils just are not fertile enough to feed crops adequately when no more nutrients than the ones in crop residues are available. External inputs of nutrients will prove to be needed for agricultural sustainability. On the ground of being a contradiction in terms, the name "low external input and sustainable agriculture" (LEISA) must, therefore, be rejected as well.

In Table 1 an example is given of the extent to which nutrient budgets in tropical farming can give rise to depletion of soil nutrient resources.

Global Nutrient Cycles with an Open End

For an effective circulation of nutrients in a global nutrient cycle, every compartment in the cycle must serve as both a sink and a source. For example, in the nitrogen cycle, the atmosphere has such a dual function. Every nitrogen atom present in a terrestrial subcycle of the global cycle will eventually return in elemental form to the atmosphere which in this context serves as a sink. Statistically viewed, it will take many centuries until any elemental nitrogen molecule

Table 1. Modal nutrient inputs and outputs for arable crops in the Kisii district of Kenya, 1990.

	Nutrients		
	N	P	K
		kg ha^{-1} yr^{-1}	
Input			
Mineral fertilizers	17	12	2
Organic manure	24	5	25
Wet and dry deposition	6	1	4
Biological N fixation	8	nr†	nr
Sedimentation	0	0	0
Output			
Removal in crops	55	10	43
Removal in crop residues	6	1	13
Leaching	41	0	9
Denitrification	28	nr	nr
Water erosion	37	10	36
Balance	-112	-3	-70

† nr = not relevant. Source: Smaling *et al.* (1993).

returning to the atmosphere, will again become eligible for being split into two nitrogen atoms which may combine with hydrogen or oxygen to potentially serve as plant food. This long residence time is explained by the fact that at any particular moment only a minute portion of the total quantity of N present on or above the earth is tied up in terrestrial ecosystems. However, at any moment every nitrogen molecule in the atmosphere is potentially available to serve as source for the formation of plant-available nitrogen compounds, such as ammonium and nitrate. However, this scenario differs widely from that of a number of other plant nutrients, among them phosphorus and potassium.

Phosphorus. In the case of phosphorus, a proper circulation of P in a global cycle is seriously hampered by the fact that the ocean floor serves as a sink, but hardly as a source. Even the low solubility of phosphate compounds cannot prevent that on a geological time scale huge quantities of the nutrient are leached from soils or -probably more important- are removed from the continents in eroded soil material entering the oceans. In these oceans the phosphorus is then partially utilized in a food chain starting with phytoplankton and ending with fish and crustaceous animals. Their bones and shells, containing relatively high concentrations of P, end up on the ocean floor and constitute there a gigantic phosphate sink of unknown dimensions. Tectonic movement of the ocean floor is responsible for an uplift of a part of these phosphate deposits, which then may appear at shallow depths on the continents, often in coastal regions. The insoluble nature of these phosphates and the fact that they are mostly not exposed to weathering prevent their dissipation over extensive land areas.

Only mining, and subsequent manufacturing of phosphate fertilizers can be instrumental in closing the global phosphorus cycle. The application of phosphate fertilizers can thus be seen as the most effective way of turning a huge phosphate sink into a phosphate source, and of returning phosphates to soils which have lost a portion of their original P reservoir due to runoff and leaching and due to export of P in marketable produce.

Potassium. The situation for potassium has its own particular features, but like in the case of phosphorus, the oceans again act as a sink. However, the high solubility of potassium salts and the low percentages of potassium in bones and shells cause most potassium in oceans to be present in soluble form. Only there where in the past inland seas and lagoons have slowly dried up, was the solubility product of potassium salts surpassed and did potassium salts precipitate on a large scale. Yet, in the present-day situation the total quantity of potassium in the world's ocean is 5000 times larger than the quantity in known continental deposits. The mining of these deposits and the manufacturing of potassium fertilizers again cause a sink to be converted into a source.

Unfortunately, potassium deposits are woefully scarce in tropical and subtropical regions. Large deposits are known to be present in the Northern hemisphere, and long supply lines make potassium fertilizers comparatively expensive in tropical countries.

More than presently is the case, potassium could be won from ocean water, but the overwhelmingly large presence of sodium in ocean water poses the problem of separating the two elements after precipitation, following evaporation of the water. The technology of separating the two in dry salt has been worked out, but the dilemma lies in the high energy requirement of the process, additional to the energy needed for evaporating off the water. Still, it can be visualized that in the future tropical countries bordering on oceans, and with plenty of sunshine, will be able to manufacture their own potassium fertilizers through direct interception of solar energy.

The Global Nitrogen Cycle

Above each hectare of earth surface 75,000 tons of nitrogen are present in the air, thus guaranteeing that nitrogen gas as basic ingredient of nitrogen compounds that can serve as plant food, will never be in low supply. A complicating factor, however, is that elemental nitrogen in the air cannot be used as such by higher plants.

As mentioned before, accomplishing a bond between nitrogen and hydrogen requires energy. Some nitrogen-fixing soil organisms acquire this energy by consuming soil organic matter as food. Other organisms live inside nodules developing on roots of leguminous plants. The nitrogen-fixing bacteria inside these nodules acquire their energy materials from the leguminous host plants, in exchange for which these plants receive fixed nitrogen from the bacteria.

Since legumes must feed the N_2-fixing bacteria with their own biomass, their dry-matter yields are usually lower than those of cereals. Also in tropical farming the disadvantages of such lower yields will have to be weighed against the advantages of not having to invest in fertilizer nitrogen needed to grow a cereal crop.

One of the additional assets of legumes that might be taken into consideration is their ability to mobilize phosphates that were added to soils as rock phosphates. Many tropical countries possess rock phosphate deposits. The relatively soft deposits are favored over the hard ones as basic materials for phosphate fertilizer manufacturing, which still takes place predominantly in developed countries. When these phosphate fertilizers are shipped back to tropical countries, the price to be paid per unit of P is much higher than that of the original basic material which as such, but then in finely ground form, can also be used as a fertilizer. Not all crops, however, are capable of utilizing ground rock phosphate. Cereals, for instance, lack the ability to absorb P from applied rock phosphate.

In contrast, leguminous crops are in a favorable position to solubilize and utilize applied rock phosphates. Their ability to grow without having to depend on soil nitrogen leads to a situation in which, due to a excess-cation-over-anion uptake pattern, legumes have an acidifying effect on the soil around their nutrient-absorbing roots. This acidification favors the solubilization of the usually alkaline rock phosphates, thus making legumes more responsive to these phosphates than most other crops.

An example of the influence of the source of nitrogen on the ability of legumes to utilize rock phosphates is given in Table 2. The phosphate used was Tilemsi rock phosphate from Mali, listed as a rock phosphate of moderate reactivity (Hammond *et al.*, 1986). Triple superphosphate was used as a reference fertilizer phosphate.

It can be seen that the soil pH increase resulting from an excess-anion-over-cation uptake pattern, when NO_3 is the N source, renders the rock phosphate completely unavailable, whereas the pH decrease resulting from symbiotic N fixation leads to a moderate availability of the rock phosphate source.

The largest quantities of symbiotically fixed nitrogen entering agricultural subcycles are to be expected from the growth of perennial forage legumes. Consequently, these species are also most effective in solubilizing rock phosphates. Inclusion of forage legume production in a farming system postulates the presence of livestock. With this statement, a first plea is made for a strenghtening of mixed farming, in the sense of a combination of arable cropping and livestock production. Further advantages of this mixed farming for the conservation of natural resources in agricultural subcycles and, thus, for the sustainability of agriculture in tropical regions will be discussed in the next section.

Table 2. The influence of variation in N source (fixed N_2 vs. NO_3) on final soil pH, P uptake from different P sources, and on dry-matter production of field bean (*Vicia faba*) in a pot experiment.

P source	N_2 fixation			NO_3 nutrition		
	pH (H_2O)	P in crop mg pot^{-1}	D. M. g pot^{-1}	(pH H_2O)	P in crop mg pot^{-1}	D. M. g pot^{-1}
Control (no P)	5.6	48d	38c	6.8	27d	30c
TSP	5.1	302a	82a	7.0	196b	98a
Tilemsi rock p.	5.3	120c	57b	6.7	31d	27c

Initial soil pH(H_2O): 6.0

Values followed by different letters differ significantly ($p<0.05$) according to Duncan's multiple-range test.

Source: (Van Diest, 1988).

Nutrient Conservation in Agricultural Subcycles

Nitrogen. One of the causes of low efficiency of applied fertilizer nitrogen is the difficulty of adjusting the supply of nitrogen to the N-absorption capacity of the crop. When in tropical regions the start of a wet season has created an opportunity for soil preparation and sowing, a part of applied fertilizer N may be lost due to leaching when shortly after emergence of the seedlings unexpectedly heavy rainfall will wash down the applied N to depths where it cannot be intercepted by the young roots. Such risks of low N efficiency are less serious in the case of legumes, as the rate of N_2 fixation is closely related to the rate of biomass production, and the fixed N is little exposed to the hazard of loss due to leaching.

Nevertheless, serious losses of N may occur when livestock is allowed to graze the forage in the field, and when in animal excreta the N is returned to the soil. Such losses usually result from the combined effects of denitrification, NH_3 volatilization and NO_3 leaching. All three types of N loss can be greatly reduced when the livestock is kept in a feedlot with a slightly sloping floor, allowing the urine to flow into an underground reservoir.

One of the most glaring obstacles to efficient recycling in tropical farming systems is the injudicious handling of animal excreta. In many cases the excreta are not collected and, when they are, they are often improperly stored or burned as fuel.

Anaerobic fermentation of excreta in a biogas digester used to be out of financial reach for many tropical smallholders. However, with the advent of plastics, to line underground trenches and to form a dome underneath in which the biogas can be collected, the building costs have been reduced to a fraction of the former price.

The technology is relatively simple, and with some help in the initial years many farmers should be able to learn how to keep the system in working condition. Eastern Asiatic nations, especially China, have set an example of efficient biogas production. It is inconceivable that thus far large donor organizations have overlooked the prospects of widespread energy conservation in small biogas installations.

The lack of interest may be due partially to unawareness of the advantages of anaerobic fermentation other than biogas production. It should be realized that in the fermentation process all nutrients present in animal excreta and in other processed waste materials can be conserved. Especially all three above mentioned forms of N loss can be reduced to a minimum.

An additional advantage is that when the effluent of the biogas digester is used as a liquid manure, the C/N ratio of the material is higher than of aerobically stored animal manure. Consequently, the release of nitrogen from the liquid manure after application proceeds more gradually, thus reducing the risk of nitrogen leaching from soil in an early part of the growing season, when the root systems of crops are still too small to intercept all nitrogen released from manure having a low C/N ratio.

Phosphorus. When a phosphate fertilizer is applied to a soil, the first crop to be grown usually absorbs only about 20% of the newly added P. The remainder is potentially available to subsequent crops. This so-called residual phosphate reacts with certain soil constituents. In such reactions, highly soluble commercial fertilizer phosphate becomes less soluble, whereas originally insoluble rock phosphates become more soluble. Consequently, the residual effects of the two sources of P upon future crops do not differ much.

Unfortunately, the crop-nutritional values of P fertilizers are still too often judged by their immediate effects on the first crop grown after application, and too little by their residual effects on subsequent crops. As a result, the agronomic values of commercial fertilizers tend to be overrated, and those of rock phosphates underrated. Many farmers in tropical countries use commercial P fertilizers, where they could make do just as well with finely ground rock phosphates, especially so when legumes are integrated into the crop rotation system. When these legumes are fed to livestock and the animal excreta enter a biogas digester, the availability to crops of P eventually leaving the digester in the effluent is almost as high as that in freshly applied superphosphate.

Due to the relative insolubility of soil phosphate compounds, leaching hazards are remote. Runoff losses can become serious only when soil mineral and organic material moves downhill in an erosion process. Since the element does not occur in gaseous forms, volatilization losses do not arise.

Still, the productivity of many farming systems in subtropical and tropical countries is hampered primarily by lack of P. In the Sahel region not water, but phosphate is often the primary yield-limiting factor (Penning *et al.*, 1980). In the rainy season, when water is plentiful, crop growth is held back by P deficiency.

Potassium. Because of lack of indigenous deposits and of slow progress in developing the technology needed to win potassium from seawater, it is to be feared that in the not so distant future in tropical farming potassium will become the crucial element. In Figure 2 it is shown that due to large increases in use of N and P fertilizers in China, the input/output balances for these two nutrients have changed from negative into positive. The resulting large yield increases have sharply raised the crop demands for K. As a result of low fertilizer K inputs, the balance for this nutrient has

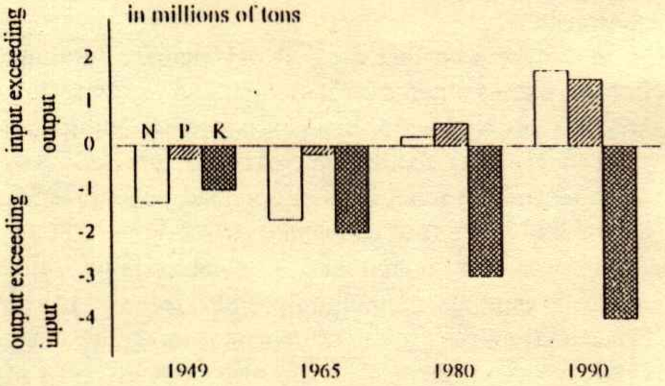

Figure 2. Nutrient input/output balance sheets for arable cropping systems in China. Source: Lin and Jin (1991).

become strongly negative. If this trend of massive soil mining will not be reversed, the efficiencies of N and P fertilizer use will decline and projected gains in crop yields will not materialize.

In such cases of negative K input/output balances it is all the more important to make optimal use of potassium in agricultural subcycles. As can be seen from the data in Table 3, contrary to N and P, most K in crops is to be found in crop residues, which may remain on the farm. This residue-K can, however, be easily washed out of these residues by rain. Through injudicious handling of crop residues large portions of potentially recyclable K can thus be lost. A very efficient way off protecting this potassium from going to waste is to feed the crop residues to livestock, along with forage legumes, and to collect the livestock excreta in a biogas digester.

Table 3. Amounts of nitrogen, phosphorus and potassium in marketable and non-marketable portions of tropical crops.

Crop	Part	Yield of D.M.	N	P	K
		t ha^{-1}	- - -	kg ha^{-1}	- - -
Rice	Grain	4.0	58	10	10
	Straw	3.3	30	2	93
Maize	Grain	4.0	63	11	16
	Stover	4.6	46	8	57
Wheat	Grain	4.0	57	11	16
	Straw	4.2	20	3	52
Pearl	Grain	4.0	80	12	20
millet	Straw	3.8	23	4	47
Cassava	Tubers	2.0	40	13	62
	Leaves and stems	2.5	25	5	25
Cotton	Seed and lint	1.7	45	11	14
	Stalks, leaves, burs	2.2	39	5	33
Soybean	Seed	1.5	90	8	30
	Straw	2.1	21	6	42

Sources: Cooke, 1985; Nijhoff, 1987.

The Benefits of Forage Legumes

Two direct advantages of inclusion of forage legumes into tropical crop rotation systems have already been mentioned:

1. Introduction of biologically fixed atmospheric nitrogen into the agricultural nutrient subcycle, and
2. The possibility of utilizing rock phosphates, which can be mobilized by the root systems of forage legumes.

If the advantages of growing forage legumes would be confined to these two assets, it would be questionable if they would offset the disadvantages of including a non-marketable crop, not fit for human consumption, into the rotation system, and of difficulties involved in converting arable farming systems into mixed farming systems.

However, other advantages of a more indirect nature can be mentioned as well, such as:

3. The possibility to produce animal manure, and to store the manure anaerobically, so that nutrient losses can be minimized.
4. The possibility to produce biogas in a digester.

Furthermore, during the period of growing a perennial forage legume, the permanent root system will give rise to an increase in soil organic matter content, and to an improvement in soil aggregation. Both characteristics are of primary importance in controlling soil erosion.

In the tropics, soil erosion is one of the greatest threats to agricultural sustainability. Keeping a soil permanently covered with vegetation is a highly effective way of reducing the destructive action of rain impact and wind and, hence, of preventing erosion. A vigorous and permanent root system keeps such a large portion of the soil entangled between its fine rootlets that the total soil body can effectively resist the destructive actions of water and wind. In addition, dead root mass serves as energy material for populations of bacteria producing mucilaginous materials, and of fungi producing mycelium tissue, which together exert an additional stabilizing effect on the soil.

The most widely publicized case of large-scale soil degradation, namely the dust storms on the North American Great Plains during the 1930s, took place in a period and in a system of low external input agriculture (LEIA). The low input was, however, combined with a sizeable output, causing large quantities of nutrients to leave the farms and finally resulting in large quantities of valuable topsoil to become lost.

If in the future tropical farmers would increase their production for foreign markets, a system of low external input agriculture would inevitably lead to soil degradation. In spite of many environmentalist' allegations to the contrary, fertilizer application, as one of the more effective ways of stimulating above-ground and below-ground biomass production, can be very helpful in reducing soil erosion.

Incorporation of perennial forage legumes into a crop rotation system will raise the organic matter content and, through improvement of soil aggregation, will increase the moisture-retention capacity of a soil. A next advantage of the growth of a forage legume is therefore:

5. The opportunity it creates to reduce soil erosion and runoff and, thus, to avoid soil degradation.

In the context of this presentation, the term "integrated farming" in the first place stands for the integration of arable cropping and livestock production. The name "integrated farming" can also represent a system in which integrated pest control is practiced, being the combination of chemical and biological pest control. Crop rotation can be viewed as a highly effective and environmentally safe way of controlling soil-borne pests and diseases. As final advantage of forage legumes in a mixed farming system can therefore be mentioned.

6. The opportunity it creates to control soil-borne pests and diseases in the years that the soil is not used for the growth of marketable crops.

The Special Case of Lowland Rice Culture

The above concept of low-cost inputs, mixed farming and anaerobic fermentation of animal excreta was presented as an example of sustainable agriculture applicable to tropical farming systems. It must, however, be kept in mind that more than half of the world population, living in South and East Asia, is largely dependent on the sustainability of lowland rice cropping systems. Nevertheless, in the context of low-cost inputs and recycling of nutrients, lowland rice cropping systems offer equally promising opportunities for nutrient acquisition and conservation.

Table 4. Dry-matter production and phosphate uptake by two cereals, as affected by variation in P source and soil physical condition in a pot experiment.

	P source			
	ZRP	TRP	TSP	Control (no P)
	Maize			
D.M. yield, g pot^{-1}	29c	38b	86a	26c
Yield of P, mg pot^{-1}	37c	47c	87b	31c
	Lowland rice			
D.M. yield, g pot^{-1}	102a	101a	101a	111a
Yield of P, mg pot^{-1}	180a	183a	214a	183a

ZRP = Zimapan rock phosphate. TRP = Tilemsi rock phosphate.
TSP = Triple superphosphate.
Values followed by different letters differ significantly ($p<0.05$) according to Duncan's multiple range test.
Source: Bako Baon and Van Diest (1989).

In between rice crops, certain fast growing legumes can be instrumental in the fixation of quantities of atmospheric nitrogen which can balance most of the nitrogen withdrawal by an average-yield rice crop. Excellent results have been reported in (Weerakoon, 1989).

The unusual situation of rice roots growing in a water-saturated soil creates conditions under which the earlier discussed, relatively insoluble rock phosphates can release enough phosphate to meet the needs of a rice crop. In addition, lowland rice has a remarkable capacity to utilize soil phosphates. The experiment reported on in Table 4 was designed primarily to investigate the P-supplying capacity of rock phosphate of low (Zimapan R.P., from Mexico) and moderate (Tilemsi R.P., from Mali) reactivity. TSP was used as reference P fertilizer. For lowland rice, the evaluation of the rock phosphates was impeded by the circumstance that the crop managed to withdraw a quantity of phosphate from soil sources which obviated the need for additional fertilizer P. The soil used was chosen for its extremely low level of available P. The control yields of dry matter and P for the maize crop confirm the low level of P availability. Nevertheless, without any fertilizer P applied the rice crop showed excellent growth and P-withdrawal capacity.

The data of Table 3 already showed that the portion of K in non-marketable crop residues is nowhere larger than for the rice crop. Hence, proper conservation of the rice straw and recycling of the nutrients in the straw will greatly reduce the need for fertilizer K to be used in lowland rice production.

CONCLUSIONS

Sizeable portions of nutrients absorbed by crops remain on the farm in crop residues. Only a proper handling of such residues can safeguard the nutrients against dissipation to places where they are irretrievable lost for future crops. A highly effective way of conserving nutrients in crop residues for use by subsequent crops is to feed the residues to livestock, along with forage legumes, and to process the animal excreta anaerobically in a biogas digester.

Judicious conservation of nutrients in agricultural subcycles of global nutrient cycles can sustain agriculture only in subsistence farming systems. When farmers start to produce for a market, they must be prepared to accept the reality that nutrients leaving the farm in marketable produce must be replenished. On a local or regional level nutrients may be returned to the farm in e.g. composted town refuse. When distant markets are served, external inputs of nutrients become mandatory. Emphasis should then be placed not so much on low external inputs of nutrients, but more on inputs of low-cost nutrient sources matching outputs of nutrients. Failure to abide by this principle will inevitably lead to soil degradation.

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EVALUATION OF FORAGE AND GRAIN LEGUMES, NO-TILL AND FERTILIZERS TO RESTORE FERTILITY DEGRADED SOILS

Evaluación de Leguminosas de Grano y Forrajeras, no Labranza y Fertilizantes para Restaurar la Fertilidad de Suelos Degradados

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SUMMARY

Enhancement and maintenance of soil fertility is essential for sustainable agriculture. The low-input sustainable agricultural systems involving forage legumes, and grain legumes in rotation with wheat, no-till practice, and fertilizers for wheat production were examined for seven years in a field experiment on a fertility degraded Vertisol in subtropical Queensland, Australia. Soil fertility restorative practices using a four year mixed grass-legume pasture (purple pigeon grass, *Setaria incrassata*; Rhodes grass, *Chloris gayana*; lucerne, *Medicago sativa;* medics, *M. scutellata* and *M. truncatula*) doubled the amounts of soil microbial biomass, mineralisable N and NO_3-N and significantly increased organic C and total N in soil. Subsequently, rate of N turnover in soil increased and higher cereal grain yields were obtained. Two year rotations of lucerne-wheat and medic-wheat and lower but similar effects on soil microbial biomass and organic matter but higher N turnover. Again cereal grain yields increased considerably. Unlike forage legume-wheat rotations, two year chickpea-wheat rotation did not maintain soil microbial biomass and organic C and N concentrations although cereal grain yields increased because of accrued N, a rapid rate of N turnover in soil and a more favorable soil water regime. No-till practice had minor effect of soil microbial biomass and organic matter but grain yields increased due to conservation of soil water in dry years. Similarly, fertilizer N effects were evident only in increased cereal grain yields and an enhanced rate of N turnover in the soil. The overall annual farm profits increased in the order: medic-wheat ($6000), lucerne-wheat ($10 000), chickpea-wheat ($16 000) and 50 kg N ha^{-1} yr^{-1} fertilizer application ($37 000). Thus, low-input sustainable agriculture is feasible using any one of the restorative practices although stability of the natural resource base (soil, biota, water) and economic benefits are likely to be attained in a combination of restorative practices.

Index words: *Crop rotations, low-input agriculture.*

RESUMEN

El mejoramiento y mantenimiento de la fertilidad del suelo es esencial para una agricultura sustentable. Los sistemas agrícolas sustentables de bajos insumos involucran leguminosas forrajeras y leguminosas de grano en rotación con trigo. Las prácticas de no labranza y fertilización sobre la producción de trigo se examinaron por siete años en un experimento de campo en el suelo Vertisol, degradado en su fertilidad, en el área subtropical de Queensland, Australia. Las prácticas restaurativas usando cuatro años de pasturas de mezcla de leguminosas y gramíneas (*Setaria incrassata, Chloris gayana, Medicago sativa, M. scutellata* y *M. truncatula*) duplicaron la cantidad de la biomasa microbiana en el suelo, el nitrógeno mineralizable y los nitratos, al mismo tiempo que se incrementó el carbono orgánico y el nitrógeno total en el suelo. Subsecuentemente se incrementó la taza de descomposición del nitrógeno en el suelo y se obtuvieron mayores rendimientos de grano de cereal. La rotación de dos años de alfalfa-trigo y medic-trigo mostró menores pero similares efectos, sobre la biomasa microbiana y la materia orgánica pero mayores sobre la descomposición de nitrógeno. De nuevo, los cereales de grano incrementaron el rendimiento considerablemente. A diferencia de la rotación del forraje de leguminosa-trigo, dos años de garbanzo-trigo no incrementaron la biomasa microbiana en el suelo y el carbono orgánico y la

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concentración de nitrógeno. No obstante, el rendimiento de grano de los cereales se incrementó debido al nitrógeno adicionado mediante la fijación, a una taza rápida de descomposición de nitrógeno en el suelo y a un régimen de humedad más favorable en el suelo. Las prácticas de no labranza tuvieron efectos menores sobre la biomasa microbiana del suelo y materia orgánica, pero los rendimientos de grano se incrementaron debido a la conservación de agua en la estación seca, similarmente los efectos del fertilizante nitrogenado fueron evidentes solo en incrementar el rendimiento de grano y en aumentar el nitrógeno en el suelo. Los ingresos globales anuales aumentaron en el orden: medic-trigo ($ 6000), alfalfa-trigo ($ 10 000), garbanzo-trigo ($ 16 000) y la aplicación de 50 kg N ha^{-1} $año^{-1}$ ($ 37 000). Por tanto, la agricultura sustentable de bajos insumos es viable usando cualquiera de las prácticas restauradoras aunque parece que estabilidad de los recursos básicos (suelo, biota, agua) y los beneficios económicos se logrará con una combinación de prácticas restauradoras.

Palabras clave: *Rotación de cultivos, agricultura de bajos insumos.*

INTRODUCTION

Increasing world population from about 1 billion in 1800, 2.5 billion in 1950 and 5.2 billion in 1993 has necessitated the development of additional land, mainly marginal in quality, especially in the tropical and subtropical regions. Potentially arable land resources are limited and cannot meet the needs of projected increase in human population. The increased production must be achieved with not only a minimum soil degradation but by reversing soil degradative trends (Lal and Stewart, 1992). Therefore, it is imperative to devise, promote and implement management strategies that will maintain, restore and in the long term enhance the soil fertility in these regions.

Principles of soil fertility restoration include the optimum use of solar radiation, temperature and available water to maximize production of plant biomass (Dalal *et al.*, 1991). Furthermore, soil fertility degradation is minimized by protecting the soil surface against erosion and structural degradation, and by integrated nutrient management, including enhanced nutrient cycling and reduced nutrients loss, while controlling disease and pollution. The incorporation of legumes is considered essential in crop rotations for sustainable agriculture in temperate zones (Power, 1989) although their roles in sustainable agriculture in subtropical and tropical regions require further study (Prasad and Goswami, 1992). Similarly no-till practice without fertilizer application does not appear to reverse soil fertility degradation in the warmer regions (Dalal, 1992). A long-term field experiment was established in 1986 on a fertility degraded Vertisol to evaluate the effectiveness of legume-based pastures and grain legumes, no-till practice and fertilizer application for fertility restoration as well as for sustainable grain production and good grain quality. We present salient features of this experiment during the first seven years on organic C, total N, mineralisable N and microbial biomass. Wheat grain yields and total N uptake (plant and yield) are presented following the fertility restorative practices. An economic assessment of the fertility restorative practices enabled a comparison of their relative performance in low-input sustainable agriculture.

MATERIALS AND METHODS

A long term field experiment was established in 1986 on a fertility-depleted Vertisol (Typic Chromustert) in a semi-arid region, with mean annual rainfall of 630 mm, in subtropical Queensland (26° 47'S, 150° 53'E), Australia. The soil contained 52 % clay, 0.7 % organic C, 0.07 % total N and pH 8.5 in the 0 - 0.1 m layer. The following treatments were examined: 1) A mixed grass-legume pasture of 4 years' duration followed by continuous wheat; the grasses and legumes were purple pigeon grass (*Setaria incrassata*), Rhodes grass (*Chloris gayana*), lucerne (*Medicago sativa*) and annual medics (*M. scutellata, M. truncatula*); 2) A two year rotation of annual medics and wheat (*Triticum aestivum*); 3) A two year rotation of lucerne and wheat; 4) A two year rotation of chickpea (*Cicer arietinum*) and wheat; 5) No-till wheat with annual application of 0, 25, and 75 kg N ha^{-1}; and 6) Conventional till wheat with annual application of 0, 25, and 75 kg N ha^{-1}. Nitrogen was applied as fertilizer urea at planting at about 5 cm depth in alternate mid-rows.

The treatments were arranged in a randomized block design with four replications. Plot dimensions were 25 m long and 6.75 m wide.

Grass-legume pastures were established in January 1986 and grown for 3.75 years. Lucerne was planted with wheat during May - July period at the rate of 2 kg ha^{-1}. After harvesting wheat, lucerne was grown for one year. Annual medics were also established under wheat and because of their self-generating nature, were planted only once. Annual dry matter and N yields of the perennial grass-legume pasture and lucerne were measured in four harvests at three monthly intervals, while in only one harvest for the annual medics. At each harvest, surplus dry matter was either removed or grazed. Since changes in soil properties were similar in both pasture management systems. Results of the cut and removed system only are reported.

The grass-legume and forage legume phases were terminated by blade ploughing (minimum soil inversion) in October each year, about six months before the planting of wheat so as to allow water recharge of the soil profile during the summer-autumn period.

Wheat and chickpea grain yields were measured from 1.75 m x 23 m central areas of all plots. After determination of grain water content, grain yields were adjusted to 12 % H_20 content. Total dry matter yields were recorded from the middle two rows, 0.25 m apart and 1 m long. Straw and grain were analyzed for their N concentration.

Weeds in the no-till treatment were controlled by herbicide spray (glyphosate and 2-4 D, amine) 2-4 times during the clean fallow period. Weed control in the conventional till treatment was achieved by 2-4 operations usually by a tined implement to approximately 100 mm depth, during the fallow period.

Five soil samples were collected from each plot with a 50 mm diameter tube sampler down to 0.1 m depth at least twice a year, one sampling soon after the crop harvest in November and the other in May before sowing. The samples were bulked, sealed in plastic bags and stored at 4 °C until analysis. Soil samples were also taken from deeper layers, down to 1.5 m depth, twice each year, and infrequently to 3 m depth for subsoil measurement of mineral N and water.

After removal of large visible pieces of plant material, a portion of soil sample from 0 - 0.1 m depth was moistened to field capacity, incubated at 22 °C for seven days and then soil microbial biomass C and N were measured using a fumigation-incubation method (Jenkinson, 1988; Jenkinson and Powlson, 1976). A K_c value of 0.41 (Anderson and Domsch, 1978) and K_n value of 0.5 (Jenkinson, 1988) was used to calculate microbial biomass C and N in soil. The unfumigated soil samples were used to determine aerobic mineralisable N. The remaining soil was dried at 30 $\pm$ 5 °C in a forced draught oven and ground < 2 mm initially, and then to < 0.25 mm for determination of total N, including NO_3-N, by a modified Kjeldahl method (Dalal *et al.*, 1984), and organic C by the Walkley-Black method adapted for spectrophotometric determination (Sims and Haby, 1971). Total N in the plant material and the grain was determined in the Kjeldahl digests using alkaline sodium isocyanurate (Crooke and Simpson, 1971). Mineral N in soil was extracted by 2 M KCl and NH_4-N and NO_3-N were determined in the extracts by automated method (Best, 1976). All results are reported on oven-dry weight basis.

Analysis of variance was performed to assess the effect of treatments on microbial biomass, organic C and total N, aerobic mineralisable N, mineral N (mostly NO_3-N), grain yield and total N yield by standard statistical techniques (Snedecor and Cochran, 1967). Time trends in soil properties were discerned by regression analysis. Economic analysis was made on a whole farm basis of mixed grain-livestock enterprises.

RESULTS AND DISCUSSION

Significance of the various soil fertility restorative practices in the low-input sustainable agriculture were evaluated in terms of time-trends in relative stability of the natural resource base (soil organic C, total N, and microbial biomass), dynamics of nutrient cycling (mineralisable N and field mineralisation rate), relative stability in crop yields and relative economic benefits (farm profitability). Relative ecological soundness of the restorative practices was examined in terms of nutrient synchrony resulting from these cultural practices.

Soil Organic C and Total N

Soil organic C content following mixed grass-legume pasture maintained for 2 to 4 years increased almost linearly with the pasture period. Organic C content increased by about 650 kg C ha^{-1} yr^{-1} in soil under grass-legume pasture compared with that under conventional cultivation. This is attributed to the continuous addition of C from surface plant materials

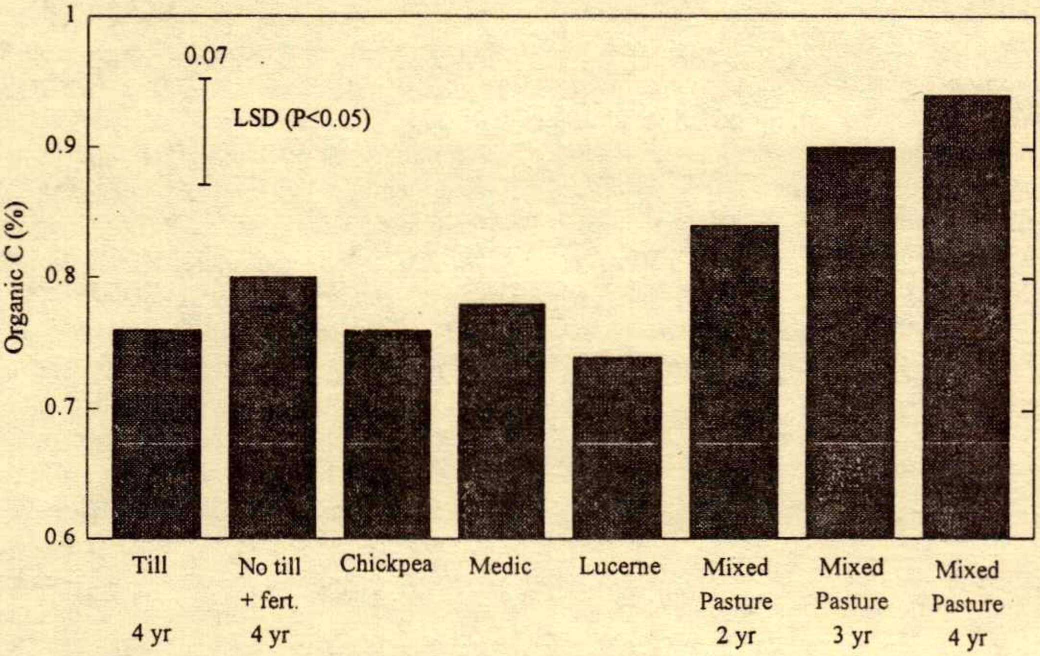

Figure 1. Organic carbon content following soil fertility restorative practices (0 to 5 cm).

and roots (Robertson *et al.*, 1993) and nitrogen accretion from legumes. The absence of cultivation may also retard organic matter decomposition.

The rate of increase in soil organic C under grass-legume pasture (Figure 1) was satisfactorily explained by the equation:

$OC_t = 1.28 + (0.76 - 1.28) \exp (0.1273 \text{ yr}), r^2 = 0.99$

Where OC_t is the organic C at time, t years. Thus, the rate of organic C accumulation in this Vertisol was relatively rapid initially and it was similar to but opposite in magnitude to that of rate of loss in organic C (-0.09 yr^{-1}) in this soil although the equilibrium value of 1.28 % organic C is much lower than the virgin soil organic C content of 2.26 % (Dalal and Mayer, 1986). This demonstrates that the grass-legume pasture system can restore organic C rapidly in fertility degraded soils.

Two-year rotation of lucerne-wheat, medic-wheat and especially chickpea-wheat had relatively small effect on soil organic C content (Figure 1). It is likely that relatively small inputs and the rapid rate of turnover of added organic C in these short-term legume rotations did not allow organic matter build-up over four years in this soil (Campbell and Zentner, 1993).

In the longer-term, however, soil total N in the two-year rotations of lucerne-wheat and medic-wheat exceeded that in the chickpea-wheat rotation and continuous conventional till wheat treatment (Figure 2). Furthermore, soil total N contents approached the initial levels after about 7 - 8 years became similar to that in the 4-year grass-legume pasture-3 year wheat treatment. Apparently, forage legumes in rotation with wheat can maintain organic matter in the long-term while chickpea-wheat rotation and continuous conventional till wheat fail to arrest the decline in organic matter arable cropping (Holford, 1980), especially when the amounts of crop residue returned to soil are low (Havlin *et al.*, 1990).

In this study, no-till practice generally had a very small effect on organic C and total N in this Vertisol (data not presented). On a Udic Pellustert, higher organic C and soil total N were measured under no-till than under conventional till (Dalal, 1989), although under both tillage practices total N declined with the period of cultivation in cereal cropping systems (Dalal, 1992). The no-till practice under continuous cereal cropping without N input therefore may not be sustainable in terms of maintaining soil organic matter in soil (Powlson and Jenkinson, 1981).

Microbial Biomass and Mineralisable N

Similar to organic C and total N, soil microbial biomass increased significantly in the grass-legume

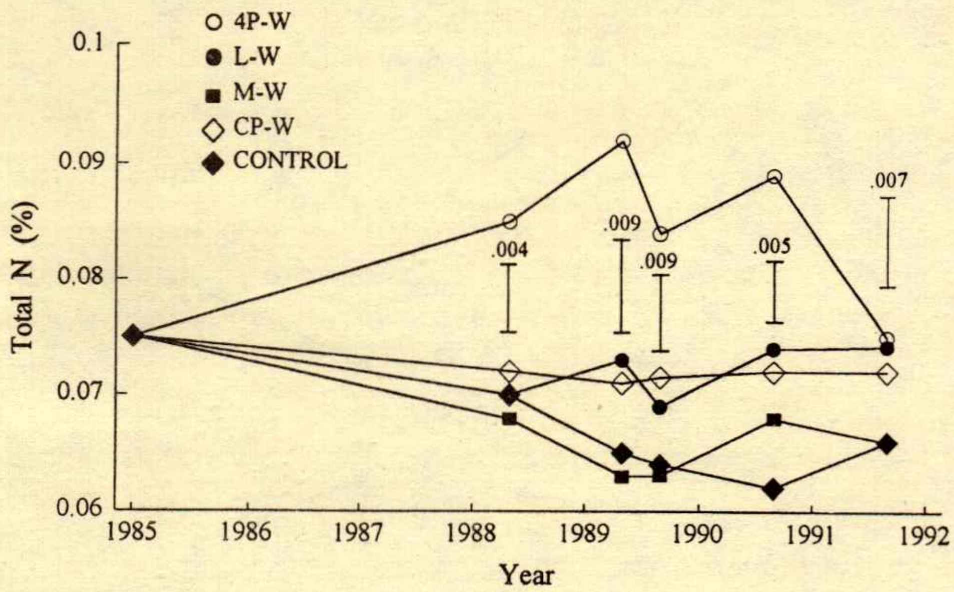

Figure 2. Trends in soil total N under 4-yr grass-legume pasture-wheat (4P-W), lucerne-wheat (L-W), medic-wheat (M-W), chickpea-wheat (CP-W) and conventional till (CT) wheat (Control).

pasture treatment (Table 1, Figure 3). Except for the microbial biomass in the medic-wheat treatment in November 1992 (Figure 3), short-term rotations of lucerne-wheat and medic-wheat had no large effect on soil microbial biomass.

Increase in microbial biomass were rapid and large in the top 0.5 cm depth (Table 1). These were 33,80 and 90 % after 1.5, 2.5, and 3.5 years of grass-legume pastures, respectively, compared with corresponding increases in organic C of 10, 20, and 24 % only. Soil microbial biomass, therefore, provided an early indication of changes in total soil organic matter due to grass-legume pasture (Powlson *et al.,* 1987).

Microbial biomass was significantly greater in the 0 - 5 cm depth in the no till treatment compared to the conventional till treatment (Table 1). In another Vertisol, no-till effects on microbial biomass were confined to only top 2.5 or 5 cm depth (Dalal *et al.,* 1991), presumably due to the accumulation of microbial C substrates on the top of the soil from the added crop residues.

Microbial quotients (microbial biomass C/total organic C) increased from 5.3 in the conventional till treatment to 8.9 in the grass-legume pasture treatment (Table 1), thus increasing the pool of labile C in soil. Microbial quotients in the top 5cm depth in this Vertisol are higher than normally encountered in soil

Table 1. Microbial biomass N and C and microbial quotient in soil under fertility restorative practices (0 to 5 cm depth).

Treatment	Microbial biomass N	Microbial biomass C	Microbial quotient
	kg ha^{-1}	kg ha^{-1}	%
Conventional till 4 yr	53	426	5.3
No-till 4 yr	66	532	6.6
Chickpea-wheat (x 2 cycles)	53	389	5.1
Medic-wheat (x 2 cycles)	64	513	6.6
Lucerne-wheat (x 2 cycles)	58	468	6.4
Grass-legume pasture 1.5 yr	71	570	6.8
Grass-legume pasture 2.5 yr	100	806	8.9
Grass-legume pasture 3.5 yr	105	837	8.9
LSD ($p < 0.05$)	13	103	1.4

(Jenkinson, 1988), presumably due to favorable seasonal conditions.

Aerobic mineralisable N increased significantly in the grass-legume treatment initially but after four years significant increases in mineralisable N were also found in the lucerne-wheat treatment as well as in 75 kg N ha^{-1} fertilizer N treatment in both conventional till and no-till practices (Table 2). Thus, substantial N cycling was evident in these treatments. The rapid cycling of N in grass-legume pasture and increased potentially mineralisable N in no-till treatments have

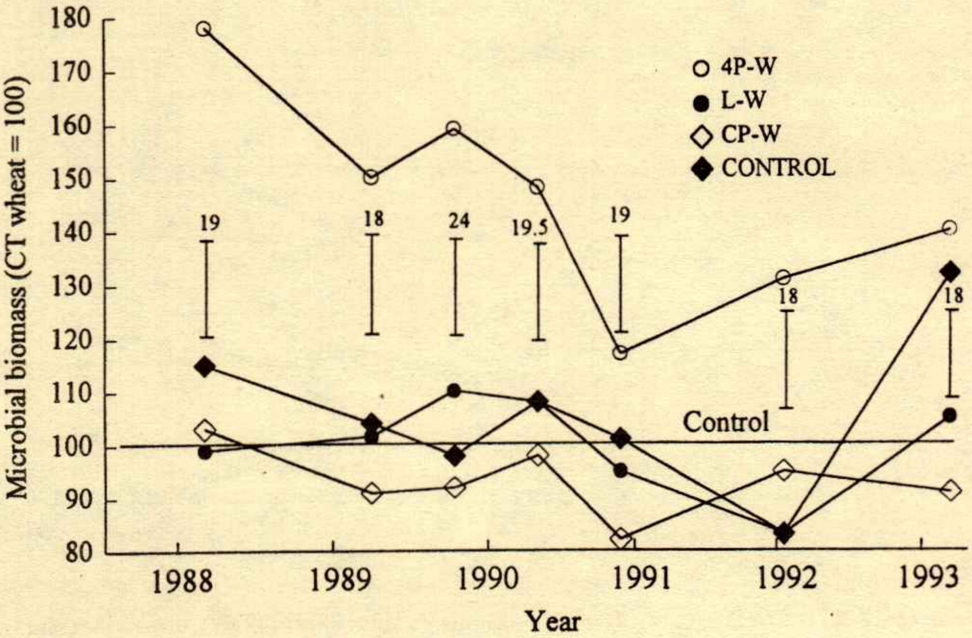

Figure 3. Trends in microbial biomass in soil under 4 yr grass-legume pasture-wheat (4P-W), lucerne-wheat (L-W), medic-wheat (M-W) and chickpea-wheat (CP-W) compared to CT wheat (Control=100).

been observed by others (Campbell and Zentner, 1993; Dalal, 1989; Robertson *et al.*, 1993).

Field Mineralisation Rates

The mineralisation rates in the field during the summer-autumn period (November 1990 to May 1992) were higher in almost all treatments compared to the conventional till soil (Table 3). Even in chickpea-wheat rotation which had no significant effects on organic C, total N or microbial biomass, mineralisation rates increased significantly. Normal fallow mineralisation rates were more rapid in the legume-cereal rotations than in cereal cropping, reflecting the rapid N turnover in legume-cereal rotations (Frankenberger *et al.*, 1985). Mineralisation rates increased where fertilizer N was applied, thus indicating an enhanced labile soil N pool. On the other hand, soil under continuous cereal cropping had almost similar mineralisation rates in the long-term, showing thereby similar long-term N cycling under different cultural practices.

Table 2. Trends in aerobic mineralisable N in soil under various fertility restorative practices (0 to 10 cm depth).

Treatment	Aerobic mineralisable N		
	May 1988	Nov. 1989	Nov. 1990
	- - - -	mg kg^{-1}	- - - -
Conventional till	13.3	5.5	17.0
Conventional till + 25 kg N ha^{-1}	15.2	5.4	17.3
Conventional till + 75 kg N ha^{-1}	14.0	7.6	28.5
No-till	13.4	4.7	15.4
No-till + 25 kg N ha^{-1}	14.5	4.5	14.0
No-till + 75 kg N ha^{-1}	14.4	10.9	33.3
Chickpea-wheat	13.8	4.2	14.0
Medic-wheat	11.9	7.3	25.3
Lucerne-wheat	13.5	20.9	27.5
Grass-legume (1986-1989) - wheat (1990)	16.2	21.7	30.2
LSD ($p < 0.05$)	2.7	9.5	8.3

Plant N Yield and N Use Efficiency

Plant N yields increased two-fold in lucerne-wheat, medic-wheat and grass-legume-wheat treatments (Table 4). Similar increases were recorded in

Table 3. Field mineralisation rates in soil under various fertility restorative practices (0 to 150 cm depth).

Treatment	Mineralisation rate	
	Nov. 1989 to May 1990†	Nov. 1990 to May 1992‡
	$kg\ ha^{-1}\ d^{-1}$	
Conventional till	0.20	0.17
Conventional till + 25 kg N ha^{-1}	0.21	0.20
Conventional till + 75 kg N ha^{-1}	0.33	0.28
No-till	0.17	0.20
No-till + 25 kg N ha^{-1}	0.23	0.18
No-till + 75 kg N ha^{-1}	0.45	0.23
Chickpea-wheat	0.31	0.24
Medic-wheat	0.45	0.24
Lucerne-wheat	0.56	0.37
Grass-legume (1986-1989) - wheat (1990)	0.46	0.26
LSD ($p < 0.05$)	0.04	0.04

† Normal clean fallow period

‡ Long-term fallow

Table 4. Total plant N yield and apparent N use efficiency in soil under various fertility restorative practices; wheat crop, 1990.

Treatment	Plant N yield	N use efficiency†
	$kg\ ha^{-1}$	%
Conventional till	41	-
Conventional till + 25 kg N ha^{-1}	55	49
Conventional till + 75 kg N ha^{-1}	96	56
No-till	47	-
No-till + 25 kg N ha^{-1}	65	77
No-till + 75 kg N ha^{-1}	93	52
Chickpea-wheat	73	87
Medic-wheat	96	70
Lucerne-wheat	90	48
Grass-legume (1986-1989) - wheat (1990)	106	85
LSD ($p < 0.05$)	8.8	-

† N use efficiency =

$$\left(\frac{\text{Plant N yield with fert N} - \text{control}}{\text{Fert. N} + \text{mineral N in fertilised treatment} - \text{mineral N in control}}\right) \times 100$$

and

$$\left(\frac{\text{Plant N yield following legume treatment} - \text{control}}{\text{Mineral N following legume treatment} - \text{mineral N in control}}\right) \times 100$$

conventional till and no-till with 75 kg N ha^{-1} fertilizer application. Plant N yield in the chickpea-wheat rotation exceeded over the conventional till wheat treatment by more than 75 %.

Except in the fertilizer N treatments, field mineralisation rate was significantly correlated with plant N yield ($r = 0.85$, $P < 0.05$) Thus, field mineralisation rate reflected N cycling in the soil-plant system satisfactorily.

Apparent nitrogen use efficiency varied from 48 to 87 % (Table 4), with a mean value of 65 %. Values vary widely, from 20 % to 80 % depending upon soil types (Holford, 1980), crop species (De *et al.,* 1985), tillage practices (Beyrouty *et al.,* 1986), source of N (Hesterman *et al.,* 1987) and seasons (Strong *et al.,* 1986). High N use efficiencies and increased N cycling in chickpea-wheat, medic-wheat and grass-legume-wheat rotations indicates their apparent usefulness in low-input-sustainable agricultural systems.

Wheat Grain Yield

Wheat grain yields in no-till treatment without fertilizer N application were essentially similar to the conventional till wheat (Figure 4). However, after the first two years, wheat grain yields in the no-till with 25 kg N ha^{-1} yr^{-1} fertilizer exceeded that in the corresponding conventional till treatment. Wheat grain yields were essentially similar in three years between no-till and conventional till treatments when 75 kg N ha^{-1} fertilizer N was applied annually but exceeded in the former in 1987 and 1992, following the drought years of 1986 and 1991. In the semi-arid regions, therefore, no-till practice is effective in some years in soil water conservation and hence increasing yields.

Wheat grain yields in chickpea-wheat and medic-wheat rotation exceeded that in conventional till wheat (Figure 5). However, in lucerne-wheat rotation wheat grain yields were depressed in 1989 and 1992, mainly due to insufficient soil water for both crop growth and grain yield. The low supply of plant available water was accentuated by the extra use of water by the preceding lucerne crop. It is likely that increased nitrate supply to wheat from the legume N, promoted rapid crop growth, and further depleting soil water supplies and leaving inadequate water for grain filling. It is, therefore, essential to utilize cultural practices that provide a suitable balance of antecedent soil water and nitrate to maximize benefits from soil fertility restorative practices.

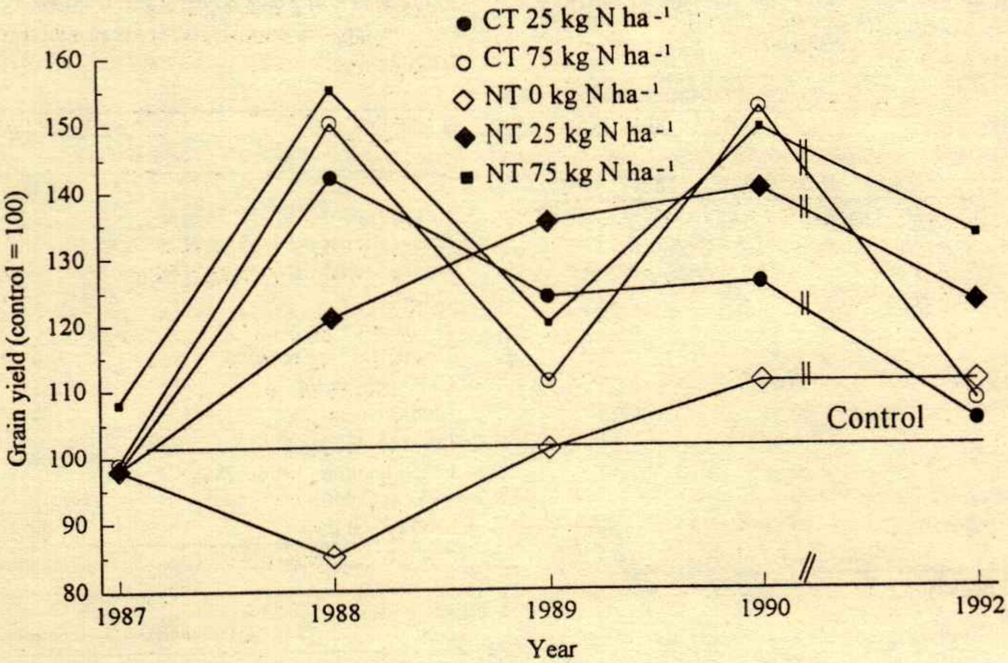

Figure 4. Effect of fertiliser N and no-tillage practice (NT) on wheat grain yield (CT wheat with 0 kg N ha^{-1} = 100).

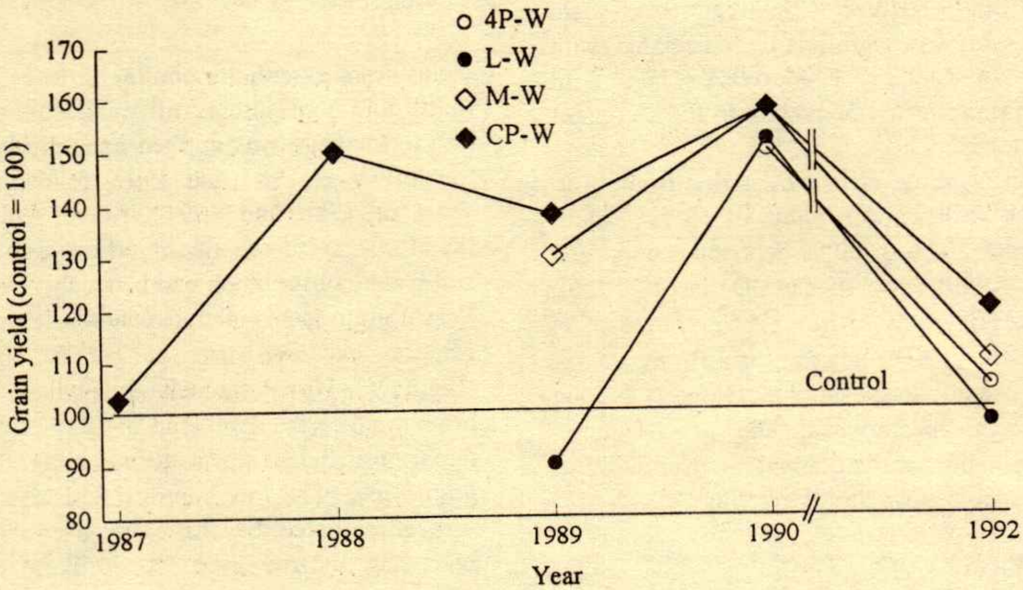

Figure 5. Effect of chickpea, annual medics, lucerne and grass-legume pasture on grain yields of following wheat crop (CT wheat with 0 kg N ha^{-1} = 100).

Farm Profitability

The total farm profitability from fertilizer N application, chickpea-wheat, lucerne-wheat and medic-wheat rotations varied considerably during the study period (Table 5). This is to be expected in highly variable rainfall regions. Overall annual farm profitability (above that of the continuous conventional

Table 5. Farm profitability from various fertility restorative practices. †

Treatment	Annual farm profitability ($'000)					
	1987	1988	1989	1990	1992	Mean
Conventional till	164	105	52	59	146	111
Conventional till + 50 kg N ha^{-1}	194	194	83	95	175	148
Chickpea-wheat	77‡	201	73	105	179	127
Lucerne-wheat	N.A.	N.A.	96	134	133	121
Medic-wheat	164	73	98	109	140	117

† Farm size, 2000 ha of that 1200 native pasture and 800 ha subjected to one of the restorative practices; inputs were varied in accordance with the necessary alterations to the farm enterprise profile in response to the changes in practice.

‡ Frost damage to chickpea.

till wheat) increased in the order: medic-wheat ($6000), lucerne-wheat ($10 000), chickpea-wheat ($16 000), and continuous conventional till wheat + 50 kg N ha^{-1} Lr^{-1} ($37 000). Low-input of fertilizer N considerably increased the annual farm profitability. Except for the frost damage in 1989, chickpea-wheat rotation also provided sustainable annual farm profits. Annual farm profits were increased but only modestly in lucerne-wheat with smaller increases in medic-wheat rotations. When it occurs, the favorable effect of chickpea or forage legumes in rotation with wheat on farm profits is due to an increase in wheat yields achieved over a smaller area thus decreasing input costs, decrease in less valuable crops and, with forage legumes, increased animal production due to improved quality feeds (Dalal *et al.*, 1991).

Understandably, no economic value was placed on other aspects of soil fertility restoration, such as reduced risk of soil erosion and runoff, and leaching, structural improvement and microbial biomass maintenance by incorporating forage legumes into cereal rotations.

CONCLUSIONS

Fertile soil in the basis of sustainable agriculture. Soil fertility restorative practices using 4 year-grass-legume pasture in this field experiment doubled the amounts of microbial biomass, mineralisable N and NO_3-N content and significantly increased soil organic C and total N. Consequently, rate of N turnover in soil increased and higher cereal grain yields were obtained. Essentially similar time-trends were evident even in a short-term forage legume-wheat rotation, especially after seven years. Unlike the forage legume-wheat rotation, chickpea-wheat rotation treatment did not maintain organic C and total N concentrations in this Vertisol, although cereal grain yield benefits were evident because of soil water advantage, accrued N and increased rate of N turnover in soil. No till practice also had minimum effect on soil organic C, total N, microbial biomass and mineralisable N. But increased cereal grain yields were obtained, especially in dry years. Fertilizer N application also had minimum effect on soil organic matter and microbial biomass but it increased the rate of N turnover in soil and cereal grain yields.

Overall increased farm profits were obtained from all the soil fertility restorative practices used in this study, although more stable and sustainable farm profits were obtained from fertilizer N application compared to the legume-cereal rotations.

This study demonstrates that low-input sustainable agriculture is feasible using any one of the restorative practices, although stability of the natural resource base (soil, biota, water) and economic benefits as well as environmental protection (gaseous emissions, leaching and chemical pollution) are likely to be attained with a combination of restorative practices. The nutrient use efficiency in low-input sustainable agricultural systems is attained by optimizing the rates of nutrient turnover commensurate with the water availability, especially in the semiarid regions. Simultaneously, nutrient balance needs to be maintained to optimize plant biomass, in essence synchrony between the soil supply and plant demand for nutrients.

Understanding the economic implications of low-input sustainable agricultural systems requires research at several levels of aggregation, including the individual component of a crop and/or a livestock enterprise, a whole farm, commodity markets, and trends in national and international agricultural economies (Madden and Dobbs, 1990). Therefore, systems analysis is required to evaluate the efficacy of various restorative practices in low-input sustainable agricultural systems in terms of trends in productivity, stability in production, trends in natural resource base, and ecological and economic indicators.

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SUITABILITY OF LOW INPUT TILLAGE SYSTEMS IN DIFFERENT SOIL TYPES

Adecuabilidad de Sistemas de Labranza de Bajos Insumos para Diferentes Tipos de Suelo

Armando S. Tasistro[1] and Eric Scopel[2]

SUMMARY

The implications of soil specificity in the adoption of conservation tillage (CT) are discussed. For this purpose the following items are considered: location and concentration of nutrients, organic matter accumulation, biological properties, soil water content, soil strength, soil temperature and soil acidity. Subsequently, alternatives for classifying the suitability of different soils for CT are analyzed.

Index words: Conservation tillage, LEISA.

RESUMEN

Se discuten las implicaciones de las características del suelo en la adopción de la labranza de conservación. Para este fin se consideran los siguientes aspectos: localización y concentración de nutrimentos, acumulación de materia orgánica, propiedades biológicas, contenido de humedad del suelo, compactación del suelo, temperatura del suelo y acidez del suelo. Subsecuentemente se analizan las alternativas para clasificar la adecuabilidad de los diferentes suelos para la labranza de conservación.

Palabras clave: Labranza de conservación, LEISA.

INTRODUCTION

Low-External-Input and Sustainable Agriculture (LEISA) systems presuppose optimal use of locally available natural and human resources. The latter include soil, water, vegetation, local plants and animals, and human labor, knowledge and skills. Moreover, LEISA is economically feasible, ecologically sound, culturally adapted and socially just. In this context, the complementarity to local resources and to meeting the above mentioned criteria condition the use of external inputs (Reijntjes *et al.*, 1992).

Conservation tillage (CT) is a wide concept embracing any tillage system that contributes to the conservation of soil water (Unger, 1978), and of soils by decreasing or preventing wind and water erosion (Lal, 1976). Additionally it also conserves the soil fertility, thus contributing to the maintenance and possibly to the increase in soil productivity. A variety of tillage options can be included in CT, all of which share two common elements: (1) A reduction in the intensity of soil movement, compared with conventional tillage, and (2) The presence of a mulch on the soil surface. Broadly speaking, all the CT alternatives can be grouped into those that can be defined as minimum tillage and no-tillage. No-tillage is the extreme case in the CT selection, in which only a narrow slot is opened in the soil where the seed is placed.

The basic idea behind CT is old (Lal, 1979) and it relates to cropping practices that have been followed for a long time, particularly by cultures in tropical areas. CT, therefore, is a low input tillage system that can be used as a significant tool in the development of LEISA systems.

It must be emphasized that CT is a mean to achieve a sustainable agricultural system. The attainment of this goal assumes a correct diagnosis in which the most limiting factors were identified.

The CT systems have additional advantages: (A) Reductions in costs, both in those directly incurred in a particular crop and in those associated with the investment in machinery, and (B) Increase in timeliness in cropping operations. CT has, however, some disadvantages: (A) Better management skills, particularly in terms of weed control and in the use of machinery (Sanchez and Miller, 1986). (B) Often requires additional outlays in herbicides (Sanchez and

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Miller, 1986) which can become quite significant. (C) Conflicts in the use of crop residues for mulches or for fodder. This is particularly relevant in dry areas, where animal food is limiting. (D) Soil specificity. The application of CT systems can be restricted by soil properties, which can be natural or related to human manipulations (Lal, 1985; Rhoton *et al.*, 1993; Triplett *et al.*, 1973).

The purpose of this paper is to discuss the implications of soil specificity in the adoption of CT systems. CT has implications in several components of the farming system, not just the soil. Thus, the consideration of the suitability of soil types to CT must not lead us to a reductionist analysis. Initially the effects that CT has on the soil's physical, chemical, and biological properties are considered, particularly from the viewpoint of soils with adverse physical or chemical conditions. Subsequently, alternatives for classifying the soils' suitability for CT are analyzed.

Effects of Conservation Tillage on Soil Properties

(A) Location and concentration of nutrients. Changes in soil chemical properties are more immediate than the physical ones. Primary changes observed in CT by various researchers (Blevins *et al.*, 1983; Centurion *et al.*, 1985; Dick *et al.*, 1986a, b; Mackay *et al.*, 1987) consist of accumulations of P, Ca, Mg, and K in the near surface zone, although there are conflicting results for Mg and K. The effects of tillage in nutrient stratification are generally negligible below 25 cm (Dick *et al.*, 1986a, b). Less information is available on the effects of tillage on micronutrients.

The pattern of change has been similarly documented for temperate and for tropical soils. Many of the latter show fertility limitations related to their very high P fixation. Some authors (Sanchez and Miller, 1986) have mentioned the need for occasional P incorporation to acid tropical soils. However, the accumulation of P in the soil surface associated with CT, could create conditions conducive to less P fixation because of the reduce contact with the rest of the soil matrix. The process of P uptake by the crop could be further helped by the increased root proliferation near the soil surface, stimulated by the more adequate temperature regime and increased moisture caused by the presence of mulches.

In a Brazilian Oxisol, for instance, fertility was improved after four years of no-tillage. Organic C, total N, pH, CEC, exchangeable bases, and P levels were higher under conservation tillage than conventional tillage, whereas the reverse was true for Al saturation (Sidiras and Pavan, 1985).

(B) Organic matter (OM) accumulation. CT practices, and particularly no-tillage, introduce several significant changes in the soil system, mainly through the disposition of residues. Although the effects on soil surface roughness and porosity are also important, their amount and duration are less marked than the effects of residue disposition (Van Doren and Triplett, 1979). Several studies have shown organic C accumulations associated with CT systems. This is because of the addition of OM through the mulch and the slower mineralization rates (see (C) Biological properties). These increases are generally restricted to the upper 5-10 cm sampling depths. Gallaher and Ferrer (1987), for instance, reported that after six years of continuous corn, the 0-5 cm depth of a fine, mixed, thermic Typic Hapludalf, had 36% more OM in no-tillage treatments than in conventional tillage treatments.

The increase in OM can have a very significant impact on the soil's structural stability. Higher levels in aggregate stability as a function of tillage intensity exist under no-till treatments (Rhoton *et al.*, 1993). Lower modulus of rupture readings have generally been recorded for no-tillage, reflecting the higher OM contents of the treatments compared with conventional tillage (Unger, 1984). The beneficial effects of OM accumulation on soil structure can be slow. The application of no-tillage is favored in soils with friable consistency over a wide range of soil water contents (Lal, 1985).

Additional OM from CT might be detrimental in Humox or Humult soils. These soils are high in OM (4-8% organic C) and have low fertility. The latter effect is due to Mn toxicity and high lime requirement (Sanchez and Miller, 1986).

(C) Biological properties. CT can dramatically affect microbial N processes and N availability. In soils under humid climates, mineralization of soil organic N, denitrification and leaching losses may be greater in no-tillage soils (Kitur *et al.*, 1984; McMahon and Thomas, 1976; Rice and Smith, 1982, 1984).

Tillage effects interact with soil types and topographical positions. Lower topographical positions might have decreased aeration due to greater soil moisture. Poor aeration in soils can cause reduced microbial decomposition that results in higher soil OM levels. Higher soil moisture contents can also reduce soil temperatures, which can also decrease N mineralization rates. Mineralized N is generally greater in well drained soils but decreases as drainage becomes limiting. Greater amounts of N mineralized can be found in the plowed well-drained soils but less in the poorly drained soils when compared to the corresponding no-tillage treatment (Rice *et al.*, 1987).

(D) Soil water content. In general terms as soil drainage improves, the need for tillage decreases. The experience shows that, for upland crops, soils with high initial porosity, (e.g., with coarse-textured surface horizons or self-mulching properties) will support the application of no-tillage. No-tillage will also be favored by soils with good internal drainage (Lal, 1985). With all the other management variables similar, crops growing on sloping, well-drained soils, will show better results with CT than with conventional tillage (Dick *et al.*, 1986b).

Excess wetness in the growing season is common on poorly drained soils and/or in udic soil moisture regimes (Valverde and Bandy, cited by Sanchez and Miller, 1986). This problem is accentuated when plant residues remain on the soil surface and especially with excessively high mulch rates that do not decompose as fast as expected. The plant mulch decreases soil temperature, so evaporation is reduced. Besides, evaporation is further reduced since the soil is not loosened with tillage (Griffith and Mannering, 1985). Yield decreases can be caused by smothering by the mulch (particularly when there are heavy residue rates), in addition to the very high soil moisture during rainy periods.

Low crop yields with CT practices on poorly drained soils can be related to decreased root densities and increased incidence and severity of soil pathogens. The fungus *Pythium graminicola* Subr. was associated with lower corn yields, while *Phytophtora* has, in turn, been associated with yield decreases in soybeans (Dick *et al.*, 1986a).

CT systems may be used in poorly drained soils without yield reductions if correct management practices are followed. These management factors include improved drainage, planting on ridges, rotation of crops, and rotation of tillage (Lal, 1985; Triplett and Van Doren, 1985).

(E) Soil strength. The continuous use of CT systems may lead to surface soil compaction, therefore, we can expect greater bulk densities (particularly under no-tillage) when compared with conventional tillage systems (Baeumer and Bakermans 1973; Lal, 1985; Rhoton *et al.*, 1993), especially with mechanized operations.

This situation may be comfounded in soils that are initially in a compacted state or that show high tendency to be so. This high soil strenght situation is applicable to subsoil compaction and to surface compaction (crusting, hardsetting soils). Surface slaking on weakly structured direct-drilled soils sometimes seriously restricts plant populations and causes a yield reduction (Cannell *et al.*, 1978). Soil compaction might be related to natural processes (presence of hard pans or high tendency for dispersion) or processes derived from human management (plow pans or sodium accumulation).

When these adverse conditions are present, ameliorating measures must be taken before starting with no-tillage: chiseling, cultivation or subsoiling (Cannell *et al.*, 1978), controlled wheel traffic, plowing when soil surface is dry, use of cover crops, planted fallows and mulches, and some degree of tillage (Sanchez and Miller, 1986).

Four tillage systems (ZT, 'Zero Tillage': direct sowing with no mulch; CT, 'Conservation Tillage': direct sowing with 2 t ha^{-1} of residues from the preceding crop as mulch; DM, 'Light Disking': light disking with mechanical weed control; and PL: disk plowing + light disking + mechanical weed control) were compared in Mexico in 1990 and 1991 (Scopel, unpublished data). This study was carried out in two contrasting soils: a brown soil (Cambisol type) with medium texture (15 % clay and 25 % silt) and a black soil (Vertisol type) with much finer texture (35 % clay and 25 % silt). The first soil tended to become compacted and hardened in the dry season, and the second showed strong tilth-forming activity with the succession of wet-dry cycles typical of the area. Under the effect of generally very aggressive rainfall, contrasting effects on soil surface compaction were observed: (A) Very rapid, irreversible deterioration in treatment ZT, (B) Rapid deterioration in treatments PL and DM but compensated by mechanical weed control during the crop cycle, and (C) Continuous but much slower deterioration in treatment CT because the soil surface was protected by crop residues. The effects on soil crusting were more readily noticed in the medium textured soil than in the one with higher clay content.

High soil strength is the main factor limiting early root growth of wheat in West. Australia. CT practices might aggravate this situation through further compaction of the surface 10 cm. Due to their high tendency to compact, some light-textured, sandy soils, traditionally regarded as 'easy' to crop, may present more potential hazards in CT than some medium textured soils (Hamblin and Tennant, 1979).

Evidence from Britain, especially in well structured clay soils, shows an improvement in the root growing conditions under CT repeated for several years. This is in spite of the higher soil strength at the surface layers of the soil compared to when they are plowed. However, water movement is faster in CT soils compared to conventional tillage, which shows the greater pore continuity after no-till (Cannell *et al.*, 1978).

(F) Soil temperature. The presence of mulches decrease soil temperatures in the top few centimeters. This effect can be adverse in temperate regions since planting can be delayed with associated yield reductions. In the tropics soil temperature during the seedling stage may be excessive, and so mulching can have a beneficial effect (Lal, 1985).

(G) Soil acidity. Permanent no-tillage, particularly with continuous use of ammoniacal N sources applied to the surface, can cause pH decreases in the top soil layers. No tillage for 22 years on Alfisols (Mollic Ochraqualf and Typic Fragiudalf) in Ohio, determined lower pH compared to minimum tillage and conventional tillage. The effect was more marked in the top 7.5 cm and under continuous corn vs. corn-soybean or corn-oats-meadow rotation (Dick *et al.*, 1986 a, b). After 10 years of continuous corn production the pH in the top 5 cm of a Maury silt loam (Typic Paleudalfs) soil maintained under no-tillage was 0.6 units lower (5.8 vs 6.4) than under conventional tillage. When N was applied at 168 kg ha^{-1} the difference was 1.0 units (4.8 vs. 5.8). Opposite results can be also observed. In an Oxisol, for instance, pH was higher under conservation tillage than conventional tillage, whereas the reverse was true for Al saturation. The complexation of the Al ions by organic substances, and the formation of low solubility products explained the beneficial effects from mulching. However, this soil management system cannot be considered as a substitute for liming in cases when a rapid correction of soil acidity is needed (Sidiras and Pavan, 1985).

Besides the negative effects of nutritional imbalances under uncontrolled soil acidity, crop yields can be further affected by increased weed competition related to triazine herbicides being inactivated more rapidly when soil pH is less than 5.5 (Blevins *et al.*, 1983; Kells *et al.*, 1980).

Surface lime applications are sufficient to correct topsoil acidity. Some degree of tillage might be necessary in acid soils of the tropic to incorporate lime at least every few years (Sanchez and Miller, 1986). Subsoil acidity, however, can be more appropriately managed through the surface application of gypsum (Shainberg *et al.*, 1993). This strategy is the most readily applicable, at least in areas where gypsum is available at reasonable cost. Either mined gypsum or phosphogypsum can be used. The latter has shown more reactivity in the soil and has the additional advantage of providing P. The application of gypsum results in: (A) Increase in subsoil Ca; (B) Decrease subsoil exchangeable Al with little or no evidence of its removal from the profile; (C) Occasional slight increases in subsoil pH; (D) Reductions in Mg and K from the topsoil downwards in the profile, particularly in sandy soils; (E) Occasional Si mobilization. The improved soil chemical environment causes greater root activity that in turn improves the soil structure and thus the soil physical conditions (Radcliffe *et al.*, 1986).

Proposals for Classifying Soils According to their Suitability for Conservation Tillage

The adoption of CT practices by farmers can be limited by the uncertainty about their success and the efforts needed to implement them successfully. Understandably, a farmer will not be willing to sacrifice short-run returns for uncertain long-run gains (Setia, 1987). Therefore, it would be useful to have guidelines to ascertain the suitability of soils for CT.

The decisions on when and how much to till the soil should be based on whether the *status quo* needs changing, the degree of change wanted, how best to achieve the desired change, how to best stabilize the new regime against subsequent return toward equilibrium (Van Doren and Triplett, 1979). Soil factors affecting the choice of tillage systems (Lal, 1979):

(A) Physical properties. Texture, structure, erodibility, bulk density and porosity, compactability, infiltration rate, moisture retention characteristics, soil-water regime, depth of the surface horizon, and rooting depth.

(B) Chemical properties. Organic matter content, cation exchange capacity, effective acidity, nutrient status and distribution in the profile, nutrient fixation capacity of the surface and subsurface horizons.

Cannell *et al.* (1978) developed guidelines to figure out the suitability of British soils for direct drilling. It is important to point out that the direct drilling system considered by these authors cannot qualify as CT since plant residues were burnt. Soil suitability was considered in terms of the likelihood of yield loss from growing crops without cultivation in comparison with conventional methods based on moldboard plows or heavy tined implements. (System based exclusively on restricting physical properties). Soil and site limiting factors were considered. The limiting soil factors were essentially physical and included: (A) Lack of tilth: Soils exhibiting a tendency for the surface layers to pack tightly either through slaking or inability of the soil to form a natural surface tilth by weathering were considered less suitable for direct drilling unless it included surface cultivation. (B) Topsoil compaction: The equilibrium level of compaction for a soil was considered a function of its natural characteristics, the amount of traffic and the moisture regime. The compaction level of soils was considered to be affected by: (1) Drainage: compaction would be less likely as drainage increased; (2) Texture: low OM sandy soils, non-calcareous soils with large amounts of silt and sandy clay loams were considered to compact readily; (3) OM content: as OM levels increased, less compaction would be expected; (4) Free lime: large quantities of naturally occurring calcium carbonate intimately mixed with the soil were associated with easier working properties; (5) Surface mulching was considered without regards to plant residues. Calcareous clays and humose or peaty soils in drier areas of the UK were considered less prone to compaction; (6) Wetness caused by slow subsoil drainage; higher susceptibility of direct drilling to waterlogging was expected because of less air-filled pore space, no possibility of water draining laterally, and lack of surface roughness. Site limiting factors included: (A) Slope: particularly in soils with low infiltration rates. (B) Excess surface water; (C) Field variability. Presumably, however, this factor would also affect conventional tillage operations. (D) Climatic limiting factors: mainly those associated with wetness. It was acknowledged that the systematization of soils based on their suitability for direct drilling would require: (A) A good data base on how soil conditions may be modified by direct drilling, and (B) The consideration of the scenario in which direct drilling was implemented on a long term basis.

Lal (1985) proposed guidelines based on the consideration of several groups of factors:

(A) Soil and water conservation. Factors included in this group were: annual cumulative erosivity, soil erodibility, soil loss tolerance, and slope. The values for soil loss tolerance consider only the direct effects to the farmer. Although it is difficult to establish general limiting values for off-site effect from soil erosion, it should be kept in mind that the latter are often more important than the direct effects. Though soil tolerance is said to be often below the 2 Mg ha^{-1} $annum^{-1}$, other ranges are considered, which can be misleading. For instance, two situations with high erosivity and soil erodibility, but one having high soil loss tolerance and high slope and the other with low soil tolerance in a flat area, can have the same cumulative rating of eight. However, the situation with high soil loss tolerance and steep slopes implies massive losses of soils with the corresponding environmental effects, whereas the one with least slope does not have a comparative environmental risk. CT would have a different fit in both situations, a fact not reflected in the score for this group of factors. Physico-chemical and nutritional limitations of the subsurface horizons are considered in evaluating the soil loss tolerance. Those limitations can, however, be overcome. The possibilities for these corrections depend on several other factors not necessarily technical in nature (e.g., availability of inputs).

(B) Hydrothermal regime. This group of factors includes: Available water holding capacity, maximum soil temperature at 5-cm depth on a bare soil, probability of a rainless period $\geq$ 10 days, and soil permeability. Soil permeability refers mostly to water movement in the profile. Conditions leading to crusting (e.g., sodicity, low soil electrolyte concentration) were not considered in detail nor the potential for their management.

(C) Soil compaction. Emphasis is placed on change in bulk density, relative compaction, and ground cover. Bulk density has been used extensively as a measure of soil compaction. However, porosity and its continuity should receive more emphasis. Conventional tillage reduces bulk density of the plow layer but destroys the continuity of pores and upsets the balance between pore sizes. As previously mentioned. CT is accompanied by increases in bulk density of the top soil layers, yet soil water movement into the soil is improved compared to conventional tillage.

(D) Nutritional properties. Three factors are considered in this group: soil pH, clay content, and cation exchange capacity. Presumably pH in the topsoil is considered, but in many Ultisols and Oxisols subsoil acidity is more important as a limiting factor for crop growth. As mentioned earlier, subsoil acidity can be corrected by surface applied gypsum. For those soils with variable charge, particularly important in the tropics, charge balance is more important than the cation exchange capacity alone. In relation to the management of heavy soils with massive structure, clayey soils with 'self-mulching' properties are considered more adaptable to no-tillage than those with massive structure and a narrow range of friable consistency.

Lal (1985) suggests that the parametric assessment of soil suitability for no-tillage system in made through the integration of all factors into one index. According to these criteria no-tillage has better chances of success when the index total less than 30; if the cumulative rating factor exceeds 45, it is advisable to use some form of mechanical method of seedbed preparation involving both primary and secondary tillage operations. It is recognized that the rating has an indicative function of the situations in which tillage is unavoidable. This need can change with time as proper agronomic practices are available for a broader set of soils and environmental conditions.

More recent alternatives in evaluating the suitability of soils for CT have been developed as expert systems (Clarke *et al.*, 1990; Steinhardt *et al.*, 1992). The expert system developed for the Central Corn Belt states in the U.S. (Indiana, Illinois, and Ohio) (Steinhardt *et al.*, 1992) estimates yields, in monoculture or rotations, for six tillage systems and in seven "Soil Tillage Management Groups". Soils are assigned to each group based on mainly physical properties such as drainage, surface texture, subsoil texture, surface color, slopes and the presence of a fragipan. Soils in a single group respond in the same way to one tillage system relative to another, so Tillage Coefficients are used to represent the relative yields expected under each tillage system in each soil group.

CONCLUSIONS

The availability of guidelines or systems to assess the suitability of soils for CT would be undoubtedly advantageous. It would help planners, decision makers, researchers, extension agents, industry, and foremost the farmers to decide about the adoption of a CT system. It must be kept in mind, however, that switching from a conventional tillage system to a CT one is accompanied by many changes in the whole production system. The effects on soil properties are very important but they are not the only ones. Weed management generally becomes a central issue, and other crop protection aspects may find greater relevance. Socio-economical components could be critical, in terms of availability of inputs, credit, and advice. Developing guidelines for soil suitability for CT practices should not be misleading. The soils in an area might be adequate for CT but another component of the production system could be limiting its adoption. Thus, it must be made perfectly clear that a soil suitability guideline considers only the impact from that resource on the adoption of CT practices. The other components of the production system must also be analyzed.

In the Mexico study the three tillage systems (ZT, CT and DM) were studied in a network of farmers' fields in addition to the trial mentioned earlier (Scopel, unpublished data). After soil preparation and sowing, the fields were worked freely by their owners in a similar way for the three tillage treatments. Yields at each site were compared with the degree to which plant water requirements were met during the cycle (real evapotranspiration/maximum evapotranspiration under the prevailing climatic conditions) calculated using a water balance model. The results (Figure 1) showed that the points corresponding to the trial situations, which differed mainly in the water use, as all other cultural conditions were non-limiting, are all in the upper part of the scatter of points. These points characterize a reference relation between production and water supply for the maize variety used (trial trend). All the points for farmers' fields are below the trial trend, whatever the soil preparation method used. This shows the effect of other limiting factors. Those points farthest from the line correspond to situations with adverse pre-flowering growth conditions. These conditions were mainly strong interference from weeds or serious mineral deficiencies, and they showed their

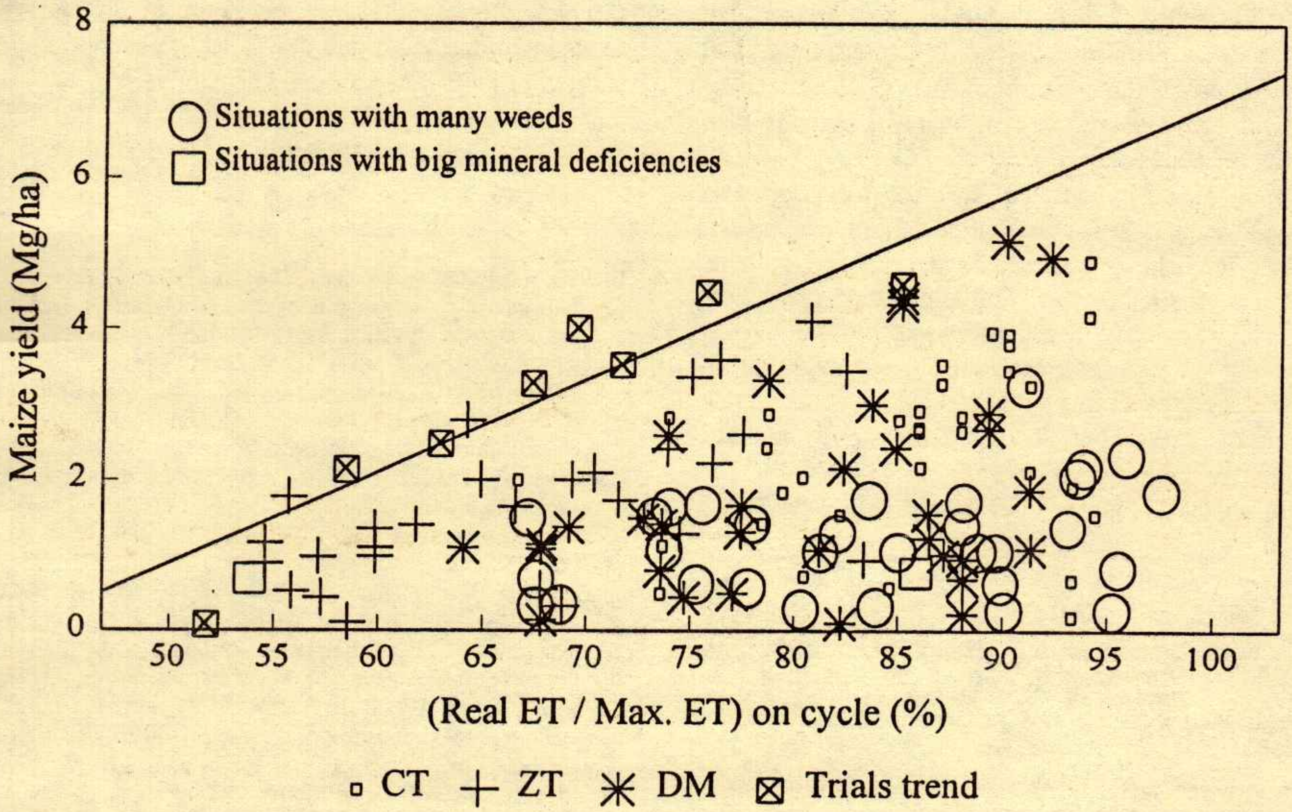

Figure 1. Field and trial observations of the effect of water supply on maize grain yield under three tillage systems (Mexico. 1990-1991). (Scopel, unpublished data).

effect even when CT was used and water requirements were met satisfactorily. Evidently in this field observations network, besides aspects concerning water use, the response to soil preparation methods was also considerably influenced by other cultural conditions (weeds, mineral deficiencies, too low planting density). Prevailing cultural conditions are in turn governed by other practices chosen by farmers (e.g., sowing, weed management and fertilization) which are chosen partly according to more general circumstances such as access to a market and credit for the purchase of the inputs necessary, and the possibility of using a CT technique. The assessment of suitability for CT, it must be stressed, cannot be done only from soil characteristics. Reference must therefore be made to a broader set of circumstances that may modify the response to the technique under given soil conditions.

In trying to have a holistic view mentioned in the previous paragraph, the expert system approach developed more recently is more appropriate than the soil suitability index considered by Lal (1985). Since the expert systems operate based on potential yields under the different tillage systems, all the other production practices associated with the tillage systems are implicitly included in the comparisons.

The development of guidelines for the selection of tillage systems requires appropriate data bases, both in quality and quantity. Unfortunately this information is normally more scarce in tropical developing areas, where CT systems are mostly needed. The development of a soil suitability index, similar to that defined by Lal (1985), is further limited by the availability of information for the factors included in that index. The application of that kind of index would require some standardization in the methods used to characterize soils. Alternatively, approximate equivalences between different factors characterizing the same soil property should be established.

Another limitation of the integral suitability index approach lies in its awarding equal importance to the soil factors. It must be stressed that CT is a tool that might help to overcome certain limitations in a production system. These critical components must be known and will then be the most important factors governing the productivity of the system. If, for instance, soil subsoil acidity is the most critical aspect, the effects of CT on its evolution should be weighed differently than the effects on another less important factor.

An additional limitation of the criteria developed so far is their lack of consideration of the time dimension. The development of sustainable agricultural systems requires a holistic approach and a long term consideration. The suitability index proposed by Lal (1985) considers the present soil condition. A soil might fall in some category according to the values of the factors as determined today, but it might change to another category as time passes by and the scores for the factors change. Changes may occur with time under CT in soil permeability and pH; soils initially considered unsuitable for CT because of inadequate values for those factors can later improve. Similarly the expert systems base their recommendation on crop yields, but no consideration is assigned to the evolution of yield when a tillage system is maintained for some time.

Environmentally, CT may sometimes have opposite effects through time. For example in loosely structured sandy soils, subject to sheet erosion, CT will be recommended if priority is awarded to soil protection, as the technique reduces runoff. However, such soils drain well and the increased internal drainage under CT may increase the leaching of nitrogen compounds and reduce productivity and potentially create other environmental problems, at crop cycle scale.

The ranking of limiting factors, and soil criteria to be used, will depend on whether stress is to be laid on short-term on long-term effects. It is true, however, that one problem associated with the concept of sustainability is its measurement. It is often difficult to measure long-term effects and their interactions, for agricultural practices.

Based on this analysis the following recommendations for assessing suitability for a CT system can be made:

(A) The most limiting factors for a sustainable agricultural system must be first identified.

(B) The potential interactions between CT and the identified limiting factors should be evaluated.

(C) According to set priorities, consider separate criteria for the characterization of the short- or long-term effects of CT on the system.

(D) An interdisciplinary analysis of all the farmer-related circumstances that may affect the adoption and success of a CT system should be conducted.

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LOW INPUT AGRICULTURE AND GREENHOUSE GAS EMISSIONS

Agricultura de Bajos Insumos y Emisión de Gases de Invernadero

Rattan Lal[1]

SUMMARY

Concentrations of radiatively-active or greenhouse gases have been steadily increasing since 1890's and more rapidly since 1950s. Important radiatively-active gases include water vapors, carbon dioxide, methane, nitrous oxide among others. Atmospheric concentration of CO_2 is at 345 ppm and is increasing at the rate of 0.5 % yr^{-1}, that of CH_4 is 90 ppb and is increasing at the rate of 0.8 % yr^{-1} and that of N_20 is 1.65 ppm and is increasing at the rate of about 1.0 % yr^{-1}. World soils constitute a major pool of organic carbon (1550 Pg of C) and can be a principal source or sink for atmospheric carbon. In comparison, soils of the tropics contain an estimate 487 Pg C or 31 % of the world soil pool. Soils play a major role in the global carbon cycle, and can be a source or sink for atmospheric carbon, depending on land use and management. Tropical ecosystems cover about 4.8×10^9 ha with principal land uses comprising 8.6 % arable, 1.0 % under permanent crops and plantations, 25.1 % under permanent pastures, 38.2 % under forest and woodlands, and remainder 27.1 % under miscellaneous land uses. Shifting cultivation and related bush fallow systems based on low-input and resource-based agricultural techniques are widely practiced in arable land use in the tropics. Similarly, native pasture species with no or little inputs, high stocking rate and uncontrolled grazing are widely practiced in tropical pastures. These resource-based systems of soil, crops and pasture management lead to accelerated erosion, land degradation, and emission of carbon and nitrogen as radiatively-active gases into the atmosphere. Total carbon emission from soil-related processes in the tropics is estimated at about 0.5 Pg C yr^{-1}. An additional 0.006 Pg N_20-N yr^{-1} is also emitted from soils of the tropics. Principal agricultural activities that lead to gaseous emission from soils include deforestation (31 %), shifting cultivation (8 %), subsistence and low-input agriculture (8 %), burning grasslands and pasture (42 %), and rice paddies (11 %). There exists a tremendous potential to reverse these trends and sequester carbon and nitrogen into soils of the tropics. Technological options to enhance soil organic carbon content include adoption of science-based agricultural practices e.g., appropriate land use, judicious and discriminate use of chemical fertilizers and organic amendments, use of improved crops and cropping systems, frequent use of planted fallows and cover crops, etc. Adoption of these systems can sequester carbon at the rate of 0.5 Pg C yr^{-1}. There also exists a large potential to sequester carbon by restoring degraded lands. Global area of degraded lands is estimated at 2×10^9 hectares. Modest increase of 0.01 % yr^{-1} in organic carbon content of these lands can lead to carbon sequestration of 2.6 Pg C yr^{-1}. Judicious management of world soils in general and soils of the tropics in particular, can render soils to be a major sink for carbon. Adoption of science-based agricultural practices can play a major role in global carbon and nitrogen budgets.

***Index words:** Carbon cycle, soil organic carbon.*

RESUMEN

La concentración de gases de invernadero o de radiación activa ha sido constantemente incrementada desde 1890 y más rápidamente desde 1950. Los gases de radiación activa más importantes incluyen vapor de agua, dióxido de carbono, metano y óxido nitroso, entre otros. La concentración atmosférica de CO_2 es de 345 ppm y se incrementa a una tasa de 0.5 % por año, la de metano es de 90 ppb y se incrementa a una tasa de 0.8 % cada año y la de óxido nitroso es de 1.65 ppm y se incrementa a una tasa aproximada de 1.0 % por año. Los suelos del mundo constituyen la reserva principal de carbono (1550 Pg de C) y puede ser la principal fuente o demanda de carbono atmosférico. En comparación, los suelos tropicales contienen un estimado de 487 Pg C ó 31 % de las reservas mundiales de carbono del suelo. El suelo juega un

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papel importante en el ciclo global de carbono y puede ser la fuente o demanda de carbono para el carbono atmosférico, dependiendo del uso de la tierra y el manejo. Los ecosistemas tropicales cubren alrededor de 4.8 x 10^9 hectáreas con tierras que se usan en 8.6 % para la agricultura, 1.0 % para cultivos permanentes de plantaciones, 25.1 % bajo pasturas permanentes, 38.2 % bajo tierras forestales y el restante 27.1 % bajo diferentes tierras de uso. El sistema de agricultura cambiante (del tipo de tumba, roza y quema) ha sido ampliamente practicado en las tierras de cultivo en los trópicos, en relación con los sistemas de cultivo de descanso basados en una agricultura de bajos insumos. Similarmente, las praderas de especies nativas sin, o con mínima, aplicación de insumos, con alto nivel de pastoreo y pastoreo descontrolado, son ampliamente explotadas en los trópicos. Este sistema de manejo ha conducido a una acelerada velocidad de degradación de la tierra y a la emisión de carbono y nitrógeno como gases de radiación activa en la atmósfera. Se estima que la emisión total de carbono en el suelo proveniente de procesos relacionados con el suelo en los trópicos aumenta 0.5 Pg de C año^{-1}. Adicionalmente, también se emiten de los suelos tropicales 0.006 Pg N_2O-N año^{-1}. Las principales actividades agrícolas que conducen a la emisión de gases de los suelos incluyen la deforestación (31 %), el sistema de cambio de cultivo (8 %), la agricultura de subsistencia y de bajos insumos (8 %), la quema de pastos y pasturas (42 %) y las tierras inundadas (11 %). Existe un tremendo potencial para revertir esas tendencias y suministrar carbono y nitrógeno en el suelo del trópico. Tecnológicamente, para mejorar el carbono orgánico del suelo se recomienda la adopción de prácticas agrícolas basadas en estudios científicos, por ejemplo, el uso apropiado de la tierra, el juicioso y discriminante uso de fertilizantes químicos y mejoradores orgánicos, el uso de cultivos y sistemas de cultivo mejorados, el uso frecuente de períodos de descanso y cultivos de cobertera, etc. La adopción de estos sistemas puede aportar 0.5 Pg de carbono de la atmósfera por año. También existe un gran potencial para obtener carbono mediante la restauración de tierras degradadas. El área global de tierras degradadas se estima que asciende a 2 x 10^9 ha. Incrementos modestos de 0.01 % por año en los niveles de carbono orgánico de estas tierras puede conducir a la obtención de 2.6 Pg de C por año. El manejo juicioso de los suelos mundiales en general y de los suelos de los trópicos en particular puede conducir a mejorar el consumo de carbono en estos. La adopción de prácticas agrícolas científicamente puede jugar un papel importante en el balance global de carbono y nitrógeno.

Palabras clave: *Ciclo de carbono, carbono orgánico del suelo.*

INTRODUCTION

Radiatively-active or greenhouse gases trap long wave radiation within the earth's atmosphere and influence global temperature. Most important radiatively-active gases comprise water vapor (H_20), carbon dioxide ($C0_2$), methane (CH_4), nitrous oxide (N_20), ozone (0_3), and chlorofluorocarbons (CFC's). Atmospheric concentrations of these gases have been steadily increasing since 1890's but more drastically since 1950's. The concentration of $C0_2$ has increased from 190 ppm in 1890 to 345 ppm in 1985 and is increasing at the rate of 0.5 % yr^{-1} or 3 Pg yr^{-1} (Pg = petagram = $1x10^{15}$ grams). The present concentration of CH_4 is 90 ppb and is increasing at the rate of 0.8 % yr^{-1}, and that of N_20 is 1.6 ppm and is increasing at the rate of 1 % yr^{-1}. Per molecule CH_4 is 25 times more effective at trapping long wave radiation than CO_2 and N_20 is approximately 200 times more effective (Bouwman, 1990).

The global carbon balance can be represented by:

$$E_c + Ed = Ai + Ou + Td \qquad (1)$$

where E_c is the emission from burning fossil fuel estimated at about 5.4 $\pm$ 0.5 Pg C yr^{-1}, Ed is the emission due to deforestation and land use and is estimated at 1.6 $\pm$ 1.0 Pg C yr^{-1}, Ai is the atmospheric increase in C and is estimated at 3.2 $\pm$ 0.1 Pg C yr^{-1}, Ou is the uptake by world's oceans and is estimated at about 2 $\pm$ 0.8 Pg C yr^{-1}, and Td is deposition in terrestrial ecosystem which for balancing Equation 1 amounts to 1.8 $\pm$ 1.4 Pg C yr^{-1}.

An important unknown in Equation 1 is the role of terrestrial ecosystems in general and that of deforestation/land use and of world soils to the global carbon budget in particular. The objective of this report is to assess the importance of low-input and subsistence agriculture in the tropics in global carbon balance and emissions of radiatively-active gases into the atmosphere.

Low-Input Agricultural Systems in the Tropics

Shifting cultivation and related bush fallow systems are practiced by some 300 million people throughout the tropics (National Research Council, 1993). This practice of subsistence agriculture is a low-input and resource-based system whereby the vegetation is slashed and burnt to release nutrient for growing several cycles of food crops. When the soil fertility is exhausted and crop yields are low, land is returned back to natural following for restoration of soil fertility and improvement of soil structure (Nye and Greenland, 1960; Okigbo and Greenland, 1978), and farmers initiate another cycle of cultivation on a new piece of land. Farmers may return to the previously cultivated land within 5 to 25 years depending on the availability of new land, demographic pressure, antecedent soil conditions and soil fertility, vegetation type, climate and several other social and cultural factors (Ruthenberg, 1980). The traditional cycle in areas of low population density is about 15 to 20 years. Shifting cultivators annually cut about 25×10^6 ha of forest in the humid and sub-humid tropics (National Research Council, 1993). Subsistence agriculture, based on human labor and animal traction with none to low external inputs, is practiced widely throughout the tropics and subtropics.

Predominant land use in the tropics involve about 420 million ha of arable land, 51 million ha of permanent crops, 1.2 billion ha of permanent pastures, 1.9 billion ha of forest and woodland, and 1.3 billion ha of other land uses (FAO, 1991). The arable land use also includes cultivation of about 145 million ha of rice in the tropics, comprising both flooded and upland cultivation systems. Because of low input cropping and uncontrolled grazing with high stocking rates, it is the soils under arable land use and permanent crops that are prone to different processes of soil degradation including decline in soil organic matter content and fertility depletion, compaction and accelerated soil erosion, hard setting and laterization, and salt buildup in the rootzone. Resource-based agriculture, based on fertility-mining practices, accentuates soil degradation.

Land Use and Dynamics of Soil Organic Carbon in the Tropics

World soils contain about 1550 Pg (1 Pg = petagram = 1×10^{15} g) of organic carbon, which is about twice that contained in the atmosphere (750 Pg), and about three times that contained in the world's biota (550 Pg) (Bohn, 1976, 1978; Buringh, 1984; Post *et al.*, 1982, 1990; Houghton and Skole, 1990; Eswaran *et al.*, 1993; Schlesinger, 1993). In comparison, soils of the tropics contain about 487 Pg of organic carbon (Table 1), or about 30 % of world soil's organic pool. Kimble *et al.* (1990) and Eswaran *et al.* (1993a, b) estimated that soils of the tropics contain about 506 Pg of organic carbon.

In arable land use, and to some extent under pasture, soil organic carbon can be rapidly mineralized and depleted by high respiration rate due to continuously high temperatures. Organic carbon is also preferentially translocated over the landscape by accelerated soil erosion as dissolved organic carbon (DOC) or particulate organic carbon (POC) in overland flow and principal drainage ways (Lal, 1993b). The change in soil organic carbon with time has been studied by Nye and Greenland (1960) and Stevenson (1982), and can be represented by:

$$\frac{dC}{dt} = -kC + a \qquad (2)$$

Where k is decomposition constant, C is soil organic carbon content at time t, and *a* is accretion constant.

Table 1. Soils of the tropics and their carbon reserves.

Soil order	Area† (10^6 ha)	Organic C in 0-10 cm depth‡ (10^{15} g)
Alfisols	800	96
Andisols	9	3
Aridisols	900	35
Entisols	400	29
Inceptisols	400	48
Mollisols	78	17
Oxisols	1100	133
Ultisols	550	66
Vertisols	131	8
Others	600	52
Total	4968	487

† Van Wambeke (1991).
‡ Lal (1993a).

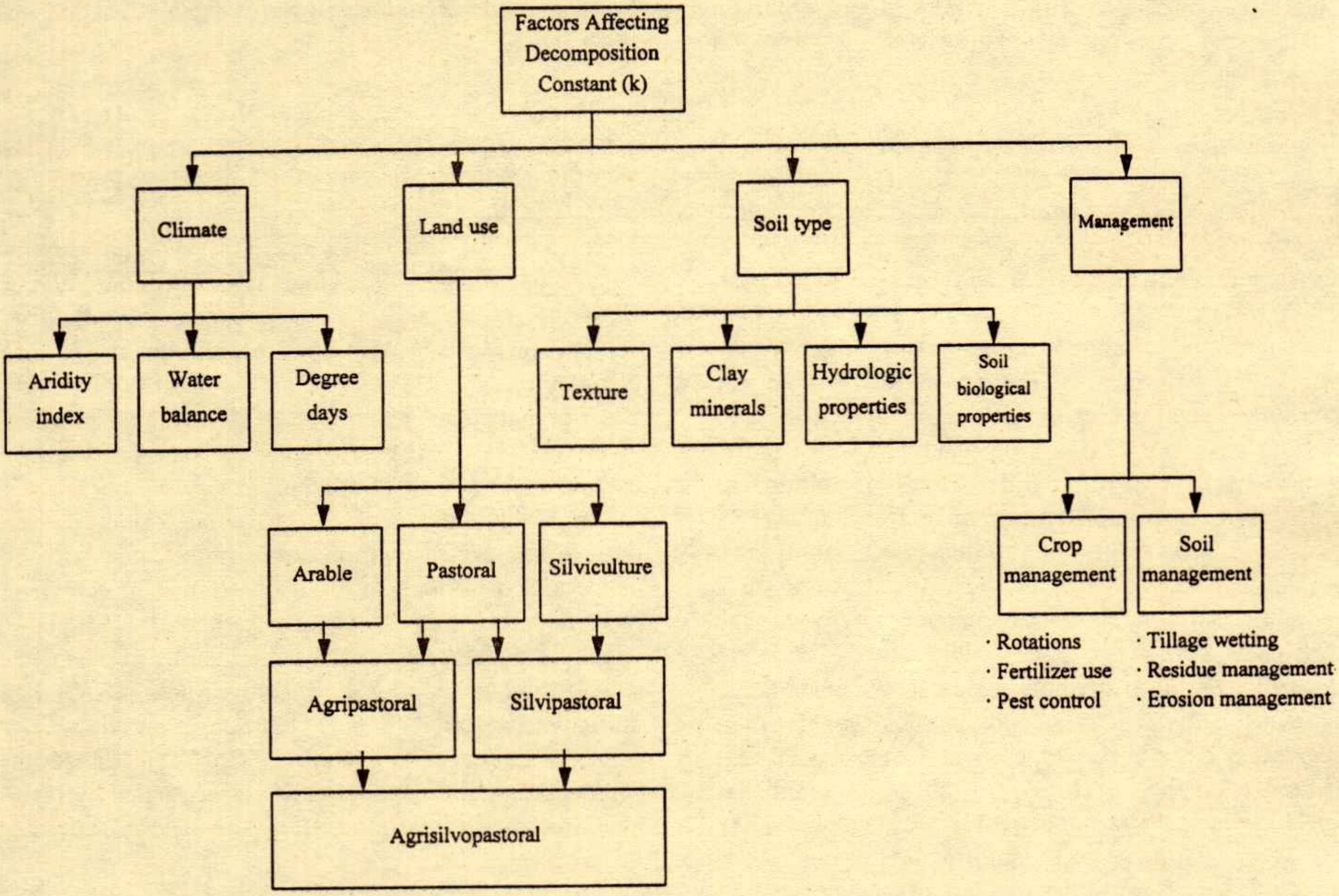

Figure 1. Environmental, land use, soil type and management factors affecting decomposition constant (k).

Constants k and a are functions of land use, management systems soil type and climate. Land use and management factors that influence magnitude of k and a are outlined in Figure 1. Important factors affecting decomposition constant k are climate, land use, soil type and management systems. Factors that **increase** decomposition constant k are high mean annual temperature as reflected by high degree days, high aridity index; arable or pastoral land use with high cropping intensity and high stocking rate; drought prone soils of coarse-texture containing predominantly low-activity clays; and plow-based intensive cropping especially with low input and fertility mining practices. In contrast, factors that **decrease** decomposition constant k are low mean annual temperature as reflected by low degree days, humid climate and low aridity index; silvicultures land use, low intensity cropping systems with frequent use of cover crops and planted fallows, and improved pastures with controlled grazing and low stocking rate; clayey soils containing predominantly high activity clays, high moisture retention and moderate permeability; and conservation tillage systems with crop residue mulch with judicious use of science-based off-farm inputs. Factors that affect the magnitude of decomposition constant k are outlined in Table 2.

Carbon Emission and Low Input Agriculture

Low input agricultural systems may be of two types: (a) those that involve low off-farm inputs but are based on practices that strengthen nutrient recycling mechanisms, and (b) those that involve fertility mining subsistence agricultural systems. The relative importance of these systems is depicted in Figure 2 and is briefly described below.

Table 2. Factors affecting decomposition constant K.

Factors	Increase k	Decrease k
A. Climate	High degree days, high mean annual temperature, high aridity index and pronounced water deficit	Low degree days, low mean annual temperature, positive water balance
B. Land use	Arable land use, high cropping intensity with none or reduced length of fallowing, traditional pastures with uncontrolled grazing and high stocking rate	Silvicultural systems and plantation crops, lengthy planted fallows with frequent use of cover crops, improved pastures with low stocking rate and controlled grazing, none or prescribed burning
C. Soil type	Coarse-textured soils with predominantly low-activity clays, low water retention capacity, excessive drainage, high soil erodibility	Heavy textured soils with predominantly high-activity clays, high water retention capacity with moderate to slow permeability, low soil erodibility
D. Management	Plow-based systems of seedbed preparation, high cropping intensity, low off-farm inputs	Conservation tillage and mulch farming techniques, science-based judicious inputs, use of cover crops and planted fallows, erosion preventive-measures, water management technique

A) Low-input systems based on nutrient recycling and high-skill management. These systems can be productive and environmentally-friendly provided that (a) nutrients harvested in crops and animals are replaced by returning crop residues, use of organic wastes, and by supplemental use of chemical fertilizers and other amendments, (b) nutrient recycling mechanisms are strengthened, and nutrients are brought in from outside the ecosystem, (c) soil nitrogen status is augmented by biological nitrogen fixation, (d) soil structure is improved through enhancement of soil biodiversity by liberal and frequent additions of biomass to the soil, and (e) soil erosion is controlled. Because farm size in the tropics is usually small, such a system can lead to intensive cropping, high biomass production per unit area and time, and possible increase in soil organic matter content. Compound farming in eastern Nigeria, and intensive vegetable and

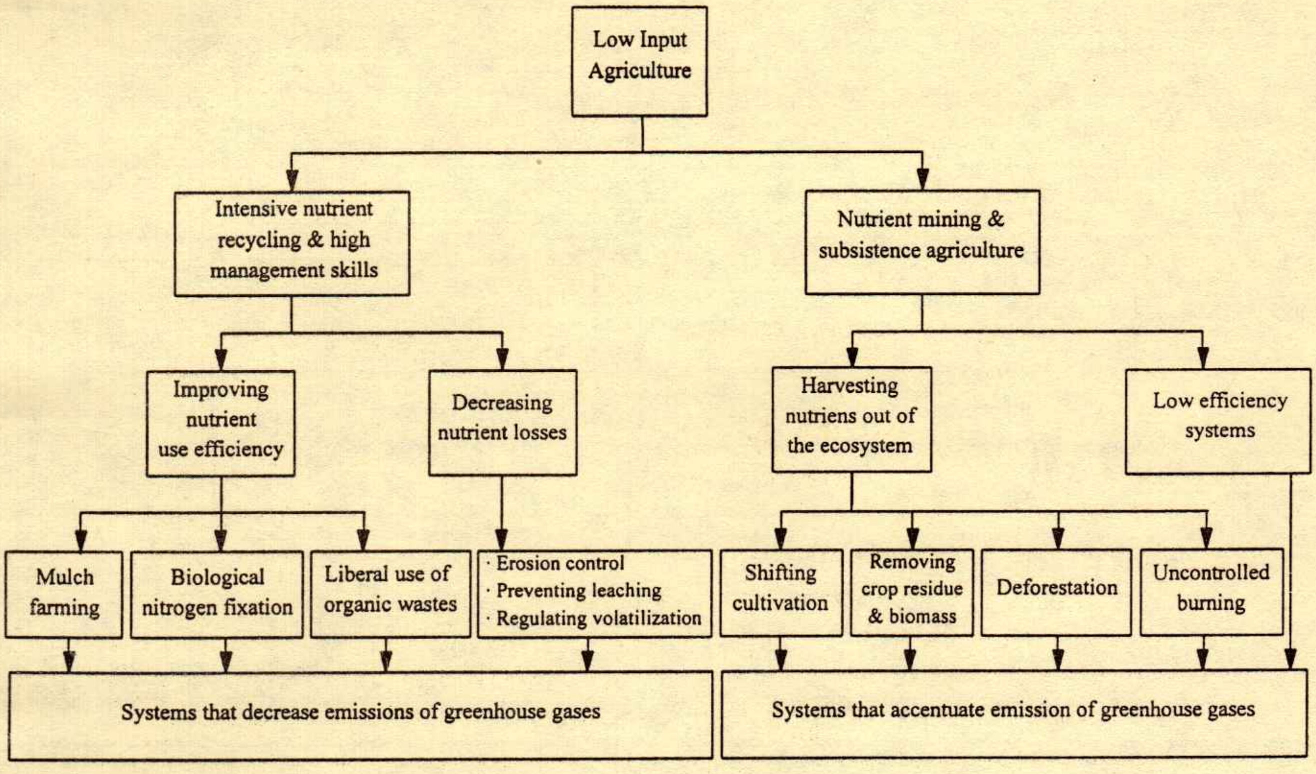

Figure 2. Low input agricultural systems in relation to their effects on emission of greenhouse gases into the atmosphere.

fodder production around urban centers in Asia and Africa are examples of such production high-skill management systems.

B) Low-input, resource-based and extensive systems. Such systems are subsistence, have low productivity, and usually degrade soil and environment (Lal, 1989). Commonly used agricultural practices for low input and subsistence systems are outlined in Figure 3. Agricultural activities have a significant effect on gaseous emissions from soil-related processes (Burke and Leshof, 1989; US Environmental Protection Agency, 1990). These practices affect gaseous emissions from soil through decomposition or biomass burning, mineralization of soil organic matter, anaerobiosis, and volatilization (Figure 4).

1. Tropical deforestation. Deforestation in the tropics

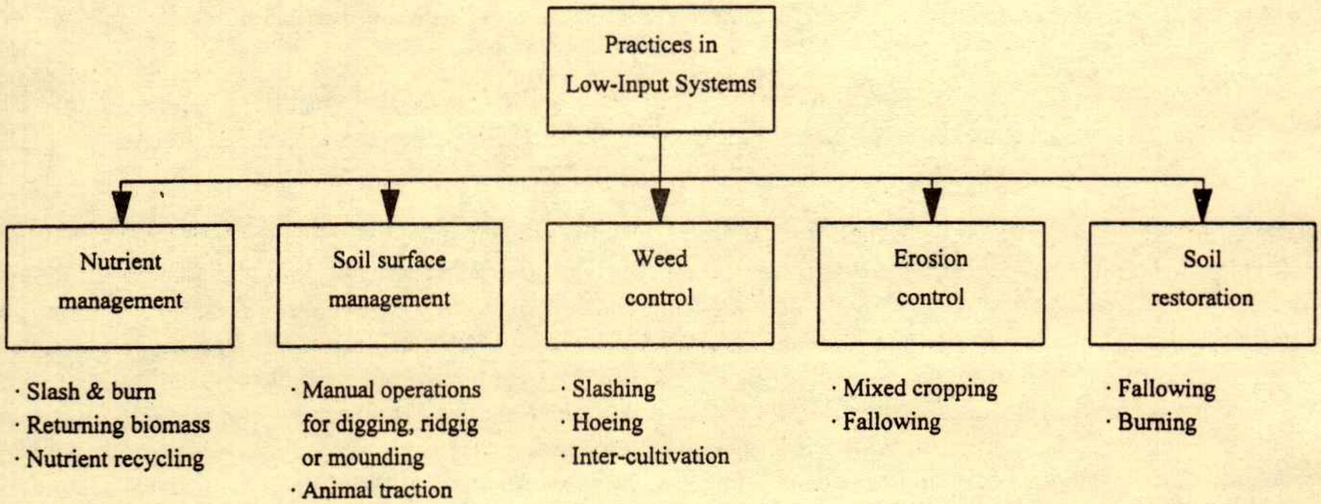

Figure 3. Commonly observed management practices in low-input and subsistence agriculture.

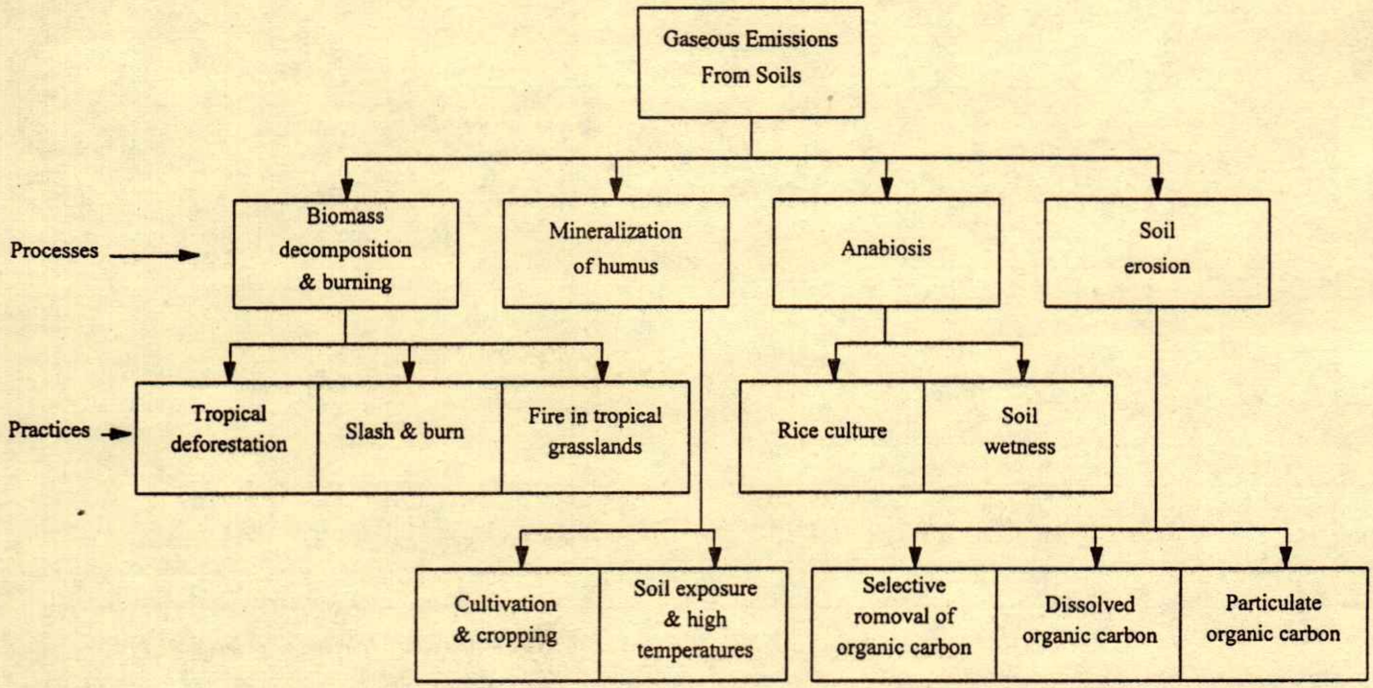

Figure 4. Processes and practices leading to emissions of radiatively-active gases from soils.

and subtropics is a major factor affecting gaseous emissions from soil-related processes. Deforestation, removal of existing vegetation cover followed by burning of biomass and leaf litter, exposes surface soil to high temperatures, high intensity rains, high winds and other climatic elements. Under these conditions, soil organic matter rapidly declines due to mineralization, accelerated erosion or leaching as dissolved or particulate organic carbon. Rate of tropical deforestation is estimated at about 20 x 10^6 ha yr^{-1} (Houghton *et al.*, 1987; Houghton, 1990; World Resources Institute, 1990-91). Deforestation leads to a rapid decline in soil organic carbon during the first two to five years. Lal (1993a) estimated that loss of organic carbon during 10-year period following deforestation may range from 11.3 Mg ha^{-1} for no-till and agroforestry based systems to 56.0 Mg ha^{-1} for plow-based systems. It was further assumed that 25 % of the cleared land was managed with no-till and agroforestry based systems and 75 % by plow-based systems. Consequently, soils from newly deforested land in the tropics release about 0.15 Pg C yr^{-1}. Assuming that a total of 2 x 10^9 ha of tropical forest has been removed over the human history, the amount of total carbon released from tropical deforestation to date is estimated at 7 Pg.

2. Shifting cultivation and subsistence agriculture. Total land area under shifting cultivation and related bush fallow systems is estimated at 150 x 10^6 ha yr^{-1}, of which 25 x 10^6 ha is newly cleared land (Lal, 1993a). Because of none or little external nutrient inputs in those systems, most nutrients removed by crops and animals are derived from mineralization of soil organic carbon or humus. Assuming that N harvested in crops is 100 kg ha^{-1} yr^{-1} of which 50 % is derived from mineralization of humus of C:N ratio of 10, it amounts to total mineralization of 500 kg ha^{-1} yr^{-1} of carbon. If 0.5 Mg ha^{-1} yr^{-1} of carbon is mineralized over 500 x 10^6 ha of arable land in the tropics, it amounts to a total emission of 0.25 Pg C yr^{-1}. Nye and Greenland (1960) estimated that loss of soil carbon may be 20 % in 200 years in a 12 year following cycle and 45 % in 100 years in a 4 year cycle. These rates of carbon loss are equivalent to 16.6 Mg ha^{-1} for a 12 year cycle and 37 Mg ha^{-1} for a 4 year cycle over the 100 year period. With total land area of 150 x 10^6 ha currently under shifting cultivation, the carbon loss from shifting cultivation and subsistence agriculture may range from 0.025 Pg yr^{-1} to 0.06 Pg yr^{-1} with an average loss of about 0.04 Pg C yr^{-1}.

3. Fire in tropical savannas and grasslands. Schlesinger (1984) estimated that tropical savannas and grassland occupy about 1.5 x 10^9 ha of land area. FAO (1991) estimated land area under permanent pastures in the tropics to be about 1.25 x 10^9 ha. Most permanent pastures are subjected to voluntary or planned burning every year. Burning may affect top 2 cm of soil surface by excessive temperatures and lead to emission of 0.5 Mg ha^{-1} yr^{-1} of carbon from soil over 25 % of tropical savannas. At this emission rate, burning of tropical savannas causes total emission of about 0.2 Pg C yr^{-1}.

4. Arable land use. Area under arable land use in the tropics is about 420 x 10^6 ha (FAO, 1991). Most of this land is used for subsistence agriculture by resource based and low-input systems of crop production. Because of low fertilizer input, soil organic matter is mineralized to release plant nutrients. Assuming that 0.15 Mg C ha^{-1} yr^{-1} is mineralized to release nutrients, the rate of C emission from arable land is about 0.04 Pg C yr^{-1}. The loss of C may be drastically less or even net addition of C into soil may occur with science-based methods of agriculture.

5. Anaerobiosis and rice cultivation. Rice is cultivated over 146 x 10^6 ha in the world and 130 x 10^6 ha in the tropics (FAO, 1991). It is usually grown in rotation with upland crops e.g., soybeans, cowpea or wheat. Carbon emission from soils during cultivation of upland crops is similar to that under arable land use. It is the carbon emission as CH_4 during rice cultivation that is a major concern in relation to emissions of radiatively-active gases. Global estimates of CH_4 flux from rice paddies are estimated at an average rate of 15 mg m^{-2} h^{-1} of CH_4 or 11.25 mg m^{-2} h^{-1} of C for a 150-day variety. This emission rate amounts to 52.8 x 10^{12} g C yr^{-1} or 70.4 x 10^{12} g CH_4 yr^{-1}. Burke and Leshof (1989) estimated global CH_4 emission of 60-170 x 10^{12} g yr^{-1}.

6. Emissions of NO_x from soil. Emissions of N_2O and other NO_x compounds may be due to release from applications of nitrogenous fertilizers and organic manures or changes in N contents of soil organic matter. Global emissions of N_2O from all sources is estimated at 15±7 x 10^{12} g N_2O - N yr^{-1}. Commonly observed emission rates may be as high as 800 mg N cm^{-2} h^{-1} (Robertson and Tiedje, 1986). The range of

emission of N_2O can be 0.3 to 135 ng N_2O-N m^{-2} δ^{-1} (Sahrawat and Keeney, 1986). Rate of denitrification of fertilizer may be as high as 20 % of the fertilizer used. Duxbury *et al.* (1982) estimated N_2O emissions of 1 kg N_2O-N ha^{-1} yr^{-1}. Total nitrogenous fertilizers used in the tropics in 16.9 x 10^6 Mg on 470 x 10^6 ha of arable land (FAO, 1991). If N_2O emissions is about 1 kg N_2O-N ha^{-1} yr^{-1} from arable land, permanent pastures and forest plus woodlands, total emission may be 3.6 x 10^{12} g N_2O - N yr^{-1} or about 25 % of the global emission. Rates of N_2O emissions are likely to increase with increasing use of nitrogenous fertilizers and organic amendments.

Total Emission of Radiatively-Active Gases from Soils of the Tropics.

The data in Table 3 and Figure 5 show total gaseous emission from tropical ecosystems amounts to about 0.5 Pg C yr^{-1} and 0.004 Pg N_20 - N yr^{-1}. Two important activities leading to C emission are deforestation of tropical rainforest and burning grasslands and savanna ecosystems. Carbon emission from soils following deforestation due to mineralization of soil organic carbon contributes to about 31 % of the total emission. An additional 42 % of the annual C emission comes from soils in tropical savannas following burning. Shifting cultivation and arable land use each contribute about 8 % of annual C emission, and CH_4 emission from rice paddies contributes about 11 % of annual C emission.

Soil Management for C Sequestration.

There are several technological options that may reverse the trend and lead to net carbon sequestration in soils of the tropics. It is important to intensify production on existing prime agricultural land and decrease the rate of tropical deforestation (Sanchez *et al.*, 1990). Furthermore, the objective is to adopt those land use systems and soil and crop management practices that decrease losses and enhance carbon sequestration in soil (Figure 6). Agricultural practices that decrease losses include:

A) Erosion-preventive measures based on (a) conservation tillage and mulch farming techniques, (b) vegetative barriers established on the contour e.g., grass strips, contour hedges of woody perennials, and (c) engineering structures of runoff management.

B) Techniques to decrease losses due to mineralization of soil organic matter (Sanchez *et al.*, 1989) including (a) measures to regulate soil temperature and moisture regimes, (b) frequent use of crop residue mulch and other biomass, and (c) techniques to enhance and manage soil fertility.

C) Methods to decrease rate of turnover of soil organic matter content including (a) appropriate land use, (b) low-intensity cropping systems, and (c) science-based inputs.

Table 3. Estimates of emissions of radiatively-active gases from soils of the tropics (modified from Lal, 1993).

Agricultural activity	Gas involved	Units	Emissions	Percent of the total
A. Carbon emissions				
Deforestation	CO_2	Pg C yr^{-1}	0.15	31
Shifting cultivation	CO_2	Pg C yr^{-1}	0.04	8
Burning grasslands	CO_2	Pg C yr^{-1}	0.20	42
Arable land	CO_2	Pg C yr^{-1}	0.04	8
Rice paddies	CH_4	Pg C yr^{-1}	0.05	11
Total C emissions		Pg C yr^{-1}	0.50	
B. Nitrogen emissions				
Fertilizer application	N_2O	Pg N_2O - N yr^{-1}	0.004	
Total N emission		Pg N_2O - N yr^{-1}	0.004	

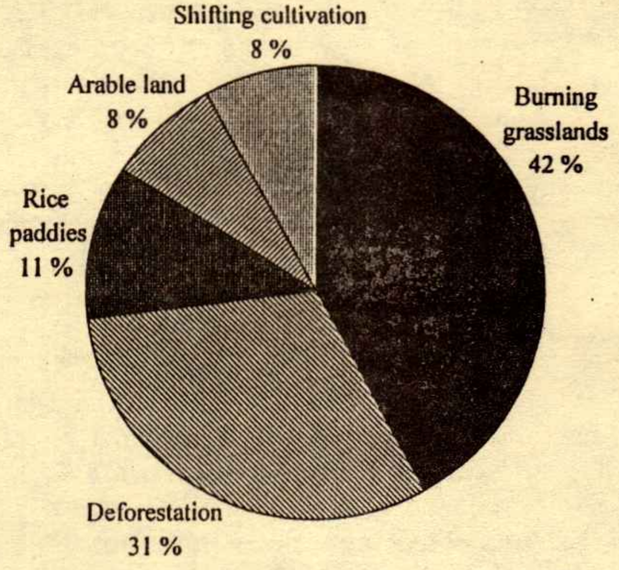

Figure 5. Carbon emission in relation to agricultural activities in the tropics (total emission is 0.50 Pg C yr^{-1}).

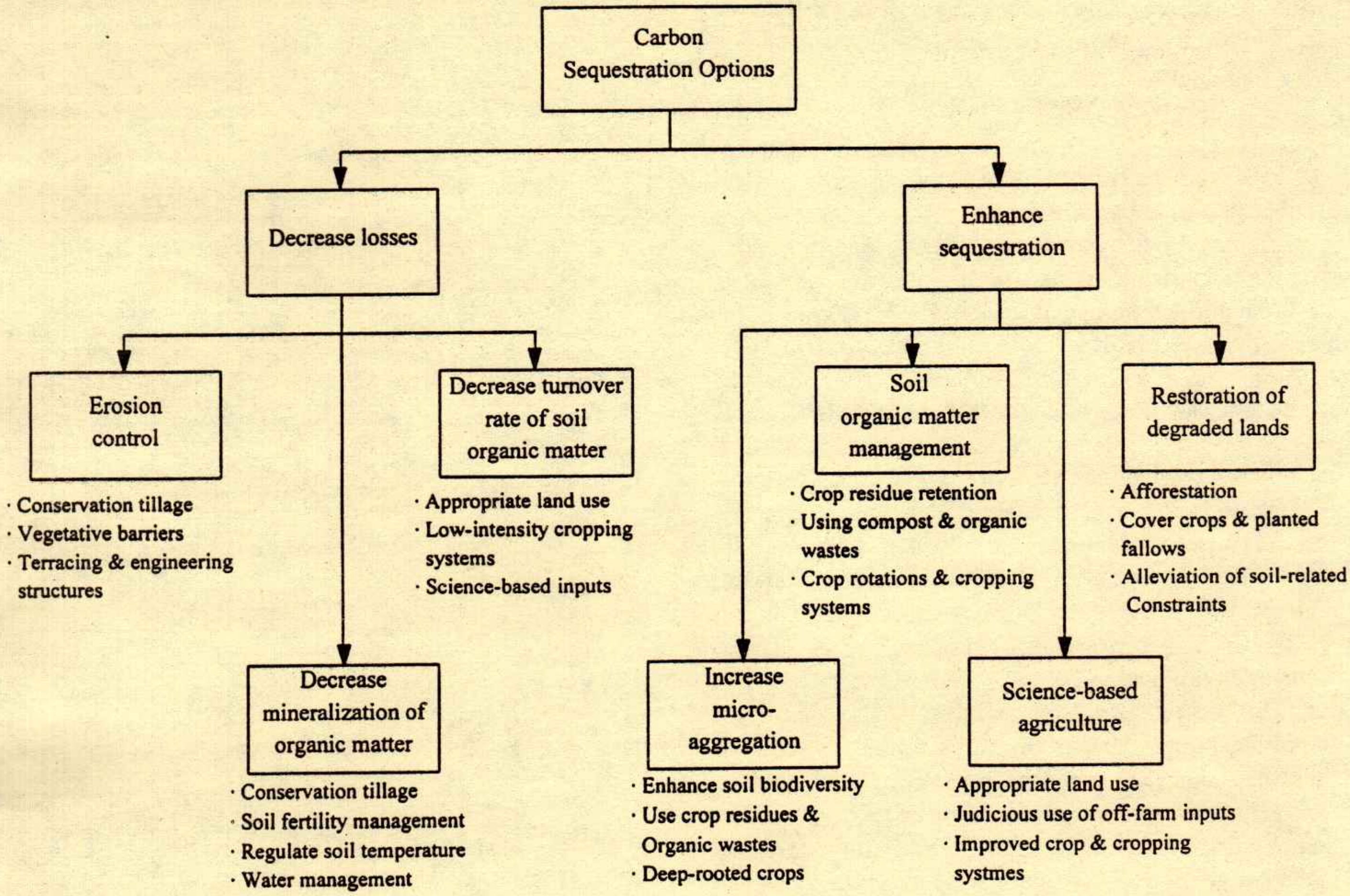

Figure 6. Technological options to enhance carbon sequestration in soils of the tropics.

There are also several agricultural practices that enhance soil organic matter content. In general, however, substantially increasing soil organic matter content in tropical ecosystems is difficult. Some possible strategies to increase soil organic matter content on a long-term basis include:

A) Increasing micro-aggregation through: (a) formation of organo-mineral complexes, (b) enhancement of soil biodiversity e.g., activity and species diversity of soil fauna including that of earthworms, (c) liberal and frequent use of crop residues and organic wastes, and (d) growing deep-rooted crops and/or trees so that soil organic matter content of the sub-soil can be increased.

B) Managing soil organic matter content through: (a) crop residue retention and liberal use of organic wastes, (b) growing cover crops and managed fallows, and (c) adoption of appropriate crops and cropping systems that produce large quantities of biomass.

C) Adopting science-based rather than resource-based agriculture through: (a) appropriate land use and productive farming/cropping systems, (b) judicious and discriminate use of chemical fertilizers and soil amendments, (c) and good farming practices that provide a continuous vegetative cover on the soil surface.

D) Restoring degraded lands through: (a) afforestation, (b) growing cover crops and managed fallows, and (c) alleviation of soil related constraints to biomass production e.g., application of fertilizers and needed plant nutrients on soils of low fertility, liming on acid soils, reclamation of salt-affected soils, drainage of extensively wet soils, etc.

Global extent of degraded soils is estimated at about 2×10^9 ha. If organic carbon contents of these soils with mean bulk density of 1.3 Mg m^{-3} can be increased by 0.01 % yr^{-1} to 1 m depth, it amounts to a carbon sequestration rate of 0.5 Pg C yr^{-1}. This much rate of increase is practically feasible with adoption of known and proven scientific technologies on hitherto degraded soils. Properly managed, restoration of degraded soils can be a major sink for carbon.

CONCLUSIONS

Land use and farming/cropping systems in the tropics may have contributed substantially to emissions of radiatively-active gases into the atmosphere. Annual rate of emissions, a first approximation presented in this report, is estimated at about 0.5 Pg C yr^{-1} and 0.004 Pg N_2O - N yr^{-1}. These emissions are related to soil degradative and fertility depletive/mining practices of widespread deforestation, shifting cultivation and related bush fallow systems, burning of grasslands and pastures, subsistence agriculture, and rice paddies.

There exists a tremendous potential to reverse these trends and sequester carbon and nitrogen into soils. Carbon sequestration involves adoption of appropriate land use, science-based agricultural techniques, and restoration of degraded lands. These techniques can lead to carbon sequestration rate of 0.5 Pg C yr^{-1}. Restoration of degraded lands is another important option for carbon sequestration in soils of the world and of the tropical ecosystems.

Preliminary estimates presented in this report can be upgraded by improving the database with regards to (a) accurate assessment of soil resource of the tropics and their distribution in different ecosystems, (b) status and dynamics of C and N change in relation to land use and management systems, and (c) measurement of fluxes of $C0_2$, CH_4 and N_20 for different management systems.

There is also an urgent need to initiate long-term land use and soil management experiments on benchmark soils in principal ecoregions of the tropics to study long-term dynamics of C and N in relation to management systems. It is also important to develop systems of land restoration, and identify policy options to facilitate and encourage adoption of these restorative measures.

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INDICATORS AND ADOPTION: ECONOMIC ISSUES IN RESEARCH ON THE SUSTAINABILITY OF AGRICULTURE

Indicadores y Adopción: Aspectos Económicos en Investigación Sobre Sostenibilidad en Agricultura

L. W. Harrington

SUMMARY

Scientists concerned with organizing research and extension for the purpose of fostering sustainable agriculture through nutrient cycling or reduced external input use must confront two sets of questions: 1) How can the influence of these practices on the sustainability of agriculture be measured? 2) What are some of the factors that influence farmer adoption of these practices, and how can adoption be encouraged? In this paper, sustainability is operationalized in terms of total productivity, defined as the value of all outputs divided by the value of all inputs, including near-term and longer-term on site economic costs, off-site economic costs, and environmental costs. Practices that feature nutrient cycling or reduced external inputs will foster sustainability when they improve total productivity. Practices that foster nutrient cycling are likely to enhance total productivity when higher near-term on-site economic costs (if any) are compensated by lower longer-term on-site costs, and off-site and environmental costs. Assessing the contribution of reduced external input use to the sustainability of agriculture is more complex. The contribution of reduced fertilizer use rates to changes in total productivity depends on the relative size and importance of changes in the different cost categories. Sustainable practices that are not attractive to farmers are of limited usefulness. Adoption has been shown to be affected by: 1) divergence between on-site and off-site costs and benefits (often affected by institutions and policy), 2) near-term vs. longer-term costs and benefits, and 3) compatibility of new technology with current farming systems, given farming system variability and complexity, and costs associated with learning about and adapting new technology. An understanding of these concepts can help focus natural resources management research on technologies likely to increase sustainability, and on practices that farmers are likely to find attractive.

Index words: *Nutrient cycling, LISA.*

RESUMEN

Los científicos se han preocupado por organizar la investigación y la extensión con el propósito de mejorar la sostenibilidad agrícola a través del ciclaje de nutrimentos y la reducción del uso de insumos externos. Este aspecto confronta dos tipos de preguntas: 1) ¿Cómo puede medirse la influencia de estas prácticas sobre la sostenibilidad de la agricultura?, y 2) ¿Cuáles son algunos de los factores que influyen la adopción de estas prácticas entre los agricultores y cómo esta adopción puede ser encausada? En este artículo la sostenibilidad es expresada en términos de productividad total, definida como el valor de todas las salidas dividido entre el valor de los insumos, incluyendo cuestiones de mediano o largo plazo en relación con los costos económicos externos al sitio y a los costos ambientales. Las prácticas que caracterizan el ciclaje de los nutrimentos y la reducción en los insumos externos va a incrementar la sostenibilidad cuando ésta incremente la productividad total. Las prácticas que mejoran el ciclaje de nutrimentos tienden a incrementar también la productividad cuando los mayores costos de corto plazo en el sitio son compensados por menores costos en largo plazo en el sitio, y costos fuera del sitio así como de los costos ambientales. Evaluar la contribución de los insumos externos producidos sobre la sostenibilidad de la agricultura es más complejo. La contribución en las dosis reducidas de fertilizantes tienden a cambiar la productividad total y dependen del tamaño relativo e importancias de los cambios en diferentes costos y categorías. La sostenibilidad de las prácticas que no

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son atractivas a los agricultores son de uso muy limitado. Se ha mostrado que la adopción es afectada por: 1) divergencia entre el costo en el sitio y el costo fuera del sitio y los beneficios (a menudo afectados por las políticas institucionales), 2) los costos de corto plazo contra los costos de largo plazo y los beneficios, 3) la compatibilidad de la nueva tecnología con las prácticas que realiza el agricultor en su sistema agrícola dado la variabilidad de los sistemas agrícolas y la complejidad y los costos asociados con el aprendizaje acerca de la nueva tecnología y acerca de su adaptación. Un entendimiento de estos conceptos puede ayudar a enfocar el manejo y la investigación de los recursos naturales sobre las tecnologías capaces de incrementar la sostenibilidad y sobre las prácticas que los agricultores consideran atractivas.

Palabras clave: *Ciclaje de nutrimentos, agricultura de bajos insumos.*

INTRODUCTION

Issues of sustainability are commanding more attention from agricultural scientists. Yet few themes can match "sustainability" for the broad range of questions that it touches and the sense of perplexity that it often engenders. The notion of sustainability encompasses population growth and pollution; deforestation and land degradation; agroecology and energy cycling; erosion and intergenerational equity; not to mention biodiversity, global warming and the ultimate fate of mankind. It is a formidable topic.

It is often claimed that the maintenance of soil productivity is essential to the sustainability of agriculture, and that nutrient cycling within agroecosystems is fundamental to this objective (Altieri, 1987). Methods suggested to foster nutrient cycling and soil conservation typically include agroforestry techniques (Garrity *et al.*, 1993) green manuring practices (Bunck, 1990), and conservation tillage techniques featuring the use of mulches (Lovejoy and Napier, 1986).

In addition, many proponents of sustainable agriculture maintain that increased use of external inputs, including fertilizers, is unwise. A number of reasons are commonly submitted, among them:

- external inputs often are used inefficiently, and yields or factor productivity frequently can be improved by more prudently applying lower levels of inputs (Byerlee 1990);
- increased use of external inputs may hide declining productivity of the natural resource base and may, in fact, hasten its decline through adverse chemical reactions (e.g., acidification);
- external inputs often pollute the environment -- in the case of fertilizer, the issue usually is one of nitrates in groundwater (Keeney, 1992);
- farmer adoption of external inputs can undermine valuable indigenous knowledge systems (Crews and Gliessman, 1991);
- external input use increasingly may tie farmers to (unreliable) external markets and reduce the self-reliance of farming communities (Altieri, 1992).

Some of the above suggestions seem reasonable; others less so. However, scientists concerned with organizing research and extension endeavors for the specific purpose of fostering sustainable agriculture through nutrient cycling or reduced external input use are likely to find themselves confronting two sets of awkward and troublesome questions:

- **Indicator and priorities.** How can the influence of increased nutrient cycling or reduce input use on the sustainability of agriculture be measured? What indicators are most suitable? How should priorities be set between research on resource-conserving technologies vs. productivity-increasing technologies?
- **Adoption.** What are some of the factors that influence farmer adoption of practices that improve farming system sustainability, possibly including those that feature nutrient cycling or reduced external input use? How can the adoption of these practices be encouraged?

The rest of this paper is devoted to a discussion of these two sets of questions. In the first section, the notion of total productivity as a measure of sustainability is introduced and applied with regard to nutrient cycling and reduced external input use. Total productivity is also shown to be useful in guiding research resource allocation. In the second section, factors are discussed that affect farmer adoption of practices commonly thought to foster sustainability. For one of these factors, an extended example is presented that draws on experience with maize-legume combinations in Mexico and Central America.

Measuring Sustainability and Setting Priorities

How can the effect of increased nutrient cycling and reduce external input use on the sustainability of agriculture be measured? Any sensible discussion of this question must begin by clarifying the concept of "sustainability". The number of definitions of sustainability (or sustainable agricultural systems) that have emerged during the last several years is too large to count. Nonetheless, most of these definitions fall into one or more of several broad approaches or conceptualizations. It should be noted that the approaches described below are not mutually exclusive. Indeed, many definitions emphasize one of them, while recognizing the others.

1. **Agroecology.** Sustainability is interpreted as system resilience, or the ability of a system to recover from stress or perturbation, largely due to system diversity featuring multiple pathways for the cycling of energy and nutrients (Conway, 1986).
2. **Stewardship.** Sustainability is interpreted human stewardship of Earth's resources, with a responsibility to non-human species as well as to future generations, to use and conserve these resources wisely. One implication is that human populations and human economic activities should be curbed (Batie, 1989).
3. **Sustainable growth**. Sustainability is interpreted as a need to minimize damage to the natural resource base while meeting growing demands for agricultural products. The definition used by the Consultative Group for International Agricultural Research (CGIAR) falls primarily into this category (CIMMYT, 1989).

One specific definition of a sustainable agriculture (falling primarily into the "sustainable growth" category) is appearing with increasing frequency and is the definition used in this paper: "**A sustainable agricultural system is one that can indefinitely meet demands for food and fiber at socially acceptable economic and environmental costs"** (Crosson, 1992). It should be understood that "economic and environmental costs" include the full range of off-farm as well as on-farm costs associated with production. Examples of economic and environmental costs of agriculture are given in Table 1.

Table 1. Economic and environmental costs of meeting growing demands for agricultural products: some examples.

Economic costs: on-site	Economic costs: off-site	Environmental costs
Near-term: Current cost of external and farmer-supplied inputs, e.g., fertilizer, labor, land, crop residues	Lost productivity through siltation of irrigation infrastructure in lowlands, associated with soil erosion in uplands	Reduced water quality and effects on public health: pesticide residues, nitrates, etc.
		Loss of biodiversity through area expansion, deforestation
Longer-term: Losses in productivity through soil erosion and soil fertility loss, or gradual salinization	Lost productivity in power generation through poor water quality, associated with soil erosion in uplands	Increased emission of greenhouse gases and possible contributions to global climate change

The advantage of the Crosson definition is that it stresses the fact that demands cannot be met, nor production increases achieved, without cost. It further highlights the notion of trade-offs among different kinds of costs, and the option of incurring costs in one region in order to reduce costs in another. As a consequence, the definition allows for the prospect that a system may be sustainable even if some of its components are not, and that a system may be required to dynamically adapt to changing external circumstance in order to be sustainable.

The Crosson definition of a sustainable agriculture system is operationalized through the notion of **total productivity**, introduced by Lynam and Herdt (1988) and Crosson and Anderson (1993). Total productivity is the sum of the value of all outputs divided by the sum of the value of all inputs, including all economic and environmental costs. Changes over time in total productivity are measured by means of index numbers, thus removing the effects of changes in relative input and output prices. Environmental costs can be difficult to quantify and value (Pearce, 1993), even though considerable methodological progress recently has been made in this area (Winpenny, 1991). Agricultural systems are deemed unsustainable when total productivity trends decline persistently, particularly when this decline is associated with resource degradation, or with undesirable environmental spillovers. A hypothetical example of an unsustainable system, featuring declining total productivity and increasing economic and environmental costs, is given in Figure 1. For further discussion on total productivity and its relationship with other indicators of sustainability, see Harrington *et al.* (1994).

It is important to note, however, that conclusions concerning "unsustainability" that are based on total productivity trends only hold true for a given level of system aggregation. When a subsystem that is

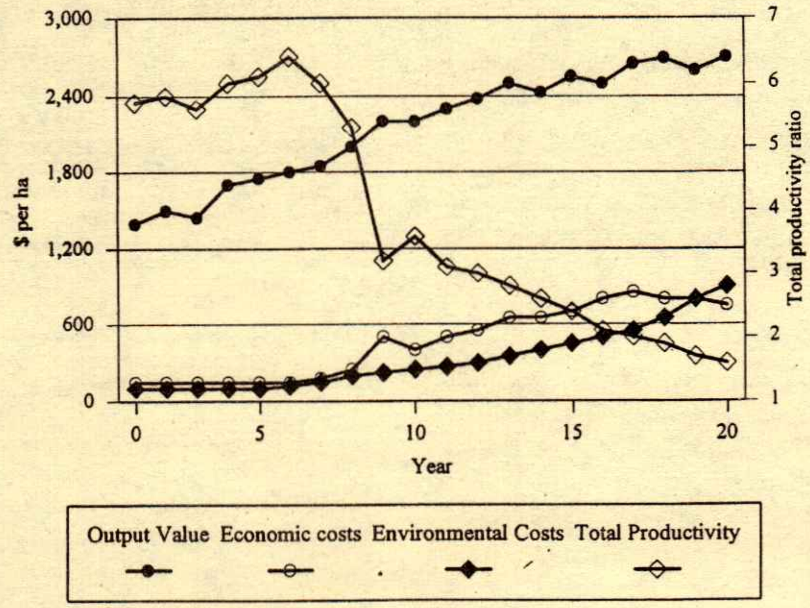

Figure 1. Estimating total productivity trends: a hypothetical illustration.

unsustainable at one level interacts in significant ways with higher level systems, conclusions with regard to unsustainability may require modification.

The following mechanisms should be kept in mind:

- a higher system level may provide opportunities for **input substitution,** e.g., declining levels of organic matter and soil fertility at the field level may be ameliorated by increased use of farm yard manure;
- a higher system level may provide opportunities for **enterprise substitution**, e.g., soil erosion associated with field crop production may be ameliorated by a shift to perennial horticultural crops made possible by investments in rural infrastructure (road, bridges);
- a higher system level may take advantage of opportunities for **trade-offs among subsystems**, e.g., investment in intensive agriculture in favored agricultural areas (possibly accompanied by environmental pollution) may, by generating income and employment and alleviating poverty, reduce the need for poor people to migrate and begin to farm fragile uplands.

Finally, an understanding of the causes of unsustainability is exceedingly important, particularly at higher levels of system aggregation, where sustainability becomes enmeshed with broad developmental issues. Unsustainability has been traced to population pressure on resources, poverty and marginalization, insecure property rights, short-term profit maximization, behavior of large landholders, and certain kinds of public policy. The interactions among these factors are complex, and space considerations prohibit a full discussion. For a more detailed assessment, see Harrington (1993).

With this conceptual framework in place, the original question now can be addressed: "How can the influence of increased nutrient cycling and reduced external input use on the sustainability of agriculture be measured?" Clearly, **practices that feature nutrient cycling or reduced external inputs will foster sustainability (at a given system level) to the extent that they also improve total productivity.** Mathematically,

$$TP = Y/(C + F + X + E) \quad (1)$$

where TP = total productivity; Y = value per ha of all outputs from a system including the value of all byproducts; C = near-term on-site economic costs including the opportunity costs of farmer owned resources; F= longer-term on-site economic costs including "user costs"; X = off-site economic costs; and E = environmental costs. Sustainable practices foster a non-decreasing trend in TP. Note that Y and all cost categories are valued at social prices, i.e., with policy-induced price distortions removed. Note also that changes over time in total productivity are measured by means of index numbers, thus removing the effects of changes in relative input and output prices.

Nutrient Cycling

Practices that foster nutrient cycling (agroforestry, green manures, conservation tillage, mulches) typically reduce environmental costs, off-site economic costs and on-site "user costs" by reducing erosion, land degradation and soil fertility loss. Moreover, by improving the technical efficiency of nutrient use, they reduce the amoount of fertilizer needed to achieve a particular level of yields (Legg *et al.*, 1989, Munson and Runge, 1990). In some instances, interventions based on agroforestry have entirely taken the place of (unavailable) inorganic fertilizers (Bannister and Nair, 1990). At the same time, however, these practices often increase other near-term on-site costs, e.g., those associated with labor and land. Green manure and agroforestry typically are less attractive to farmers when labor is expensive and when the opportunity costs of land are high (Fujisaka, 1993; Buckles *et al.*, 1992). Similarly, conservation tillage and the use of mulches usually are less attractive when the value of crop residues is high, e.g., when their feed use is important (Tripp *et al.*, 1993).

These practices can be said to foster sustainability when total productivity is increasing, i.e., when **higher** near-term on-site economic cost (if any) are compensated by **lower** user costs, or lower off-site and environmental costs. Although detailed empirical estimated of costs and returns to nutrient cycling are rare, it is usually assumed (using the language of Equation 1) that reductions in X, E and F more than compensate for increases in C and declines (if any) in Y. Generally, farmers give more weight to Y and C than to X, E and F; hence they are likely to underinvest in practices that favor nutrient cycling. Note that this analysis is confined to the level of a subsystem and ignores possible interactions among system levels.

Reduced External Input Use

The introduction of practices that foster nutrient cycling does not rule out the judicious use of external inputs (Juo and Kang, 1989). However, reduced external input use is often advocated for its own sake. The extent to which sustainability is fostered by reduced external input use once again depends on its effect on total productivity.

Near-term on-site economic costs. The argument can be made that reduced fertilizer use rates contribute, under some conditions, to a reduction in near-term on-site economic costs and thereby to improvements in total productivity and sustainability. A favorable effect on total productivity is most obvious when a reduction in fertilizer use rates is combined with improved technical efficiency (often associated with practices that foster nutrient cycling such as the ones described above). Under these conditions, reduced fertilizer use leads to little or no yield sacrifice, and total productivity is increased as on-site economic costs falls. However, reduced fertilizer use rates may also result in yield (and gross revenue) declines that outweigh the savings on fertilizer purchase, leading to declining total productivity. For example, when soil fertility is highly complementary with the use of other inputs (e.g., improved varieties), reduced fertilizer use rates can have dramatic negative effects on system productivity (Ngambeki *et al.*,1990).

Longer-term on-site economic costs. Reduced inorganic fertilizer use imposes no serious longer-term on-site economic costs when nutrient cycling practices take the place of external inputs. When nutrient cycling methods are ineffective, however, reduced fertilizer use rates may foster a gradual loss of system productivity. For example, pumping of nutrients from subsoil layers by agroforestry systems cannot substitute for the use of inorganic fertilizers when the fertility of subsoil layers is low (Juo and Kang, 1989). Increased inorganic fertilizer inputs may even be needed at times to make nutrient cycling methods more feasible. For example, conservation tillage and mulching practices have been judged as more workable when crops are adequately fertilized, increasing crop residue biomass to levels sufficient for both livestock feed and mulch (Powell and Williams, 1993). This can cause organic matter to build up more rapidly through the increased availability of farm yard manure as well as more dense mulch covers.

Reduced fertilizer use rates may actually exacerbate the deterioration in land quality associated with the long term use of specific systems. For example, recent evidence from Asia suggest that the quantity of soil organic matter typically is maintained in intensive irrigated rice systems -- but that its quality changes, gradually reducing the capacity of the soil to supply nitrogen to plants. Without modifications in nitrogen management (often involving temporarily increased nitrogen use rates), longer-term system productivity declines over time (Cassman and Pingali, 1993).

Finally, much of the apprehension surrounding a reliance on inorganic fertilizer in agricultural systems is founded on the likelihood that energy sources for producing fertilizer may be exhausted (or, more realistically, priced out of agricultural uses) within the next few decades. Such price would raise the longer-term economic costs of meeting agricultural production requirements and would thereby reduce sustainability. In this regard, it should be noted that agricultural uses account for only 1 % of fossil fuel utilization even in developed countries, and that significant shortages are likely to stimulate major adjustments in fuel use in non-agricultural sectors, e.g., transportation (Barker and Chapman, 1988). It seems unlikely that fertilizers will become unavailable because of energy shortages. The prospect that depletion of nonrenewable sources of phosphate and potash may eventually limit agricultural system productivity is ignored in this paper.

Off-site economic and environmental costs. Off-site effects of reduced (organic as well as inorganic) fertilizer use rates may be more important than on-site effects. Pollution of groundwater by nitrates and possible effects on public health constitute a major public policy issue in developed countries (Libby, 1990). It seems sensible to assume that reduced fertilizer use in many instances can contribute to improved surface and subsurface water quality, to improved quality of downstream river and coastal ecosystems, and to improved public health. More efficient use of fertilizer at reduced rates may also decrease agriculture's contribution to global emissions of greenhouse gases. The environmental costs of using fertilizer to meet growing demands for agricultural products cannot be ignored.

There are also other, relatively subtle, off-site economic and environmental effects of fertilizer use. Many of these hinge on links among fertilizer use, farming system productivity, employment generation, and poverty alleviation. Acheampong (1992), for example, claims that restoring soil fertility in West Africa is needed to reverse a downward trend in crop production and rural underemployment. His findings suggest that fertilizer use encourages the adoption of additional yield-enhancing technologies, creates jobs for the rural unemployed and underemployed and provides incentives for land conservation and community development initiatives. Similarly, Jha and Hojjati (1993) observe that fertilizer on local maize on smallholder farmers in Eastern Zambia has been a stepping stone in the transition to more diversified and productive farming systems.

Finally, it should be noted that reduced fertilizer use rates may require an expansion of cropped area in order to meet increased demands for agricultural products. When reduced fertilizer use rates lead to declining crop and forage yields, a larger cropped area is necessary to produce equivalent levels of output. (Alternatively, food prices may be allowed to increase, hurting low-income urban and rural consumers). Cropped area expansion driven by stagnant productivity in existing agricultural areas is likely to be concentrated in forest margins or other fragile areas, accelerating biodiversity loss and land degradation.

Assessing the contribution of reduced external input use to the sustainability of agriculture is obviously a complex business. Sustainability is enhanced when total productivity trends are improved, but the contribution of reduced fertilizer use rates to increased total productivity depends on the relative size and importance of effects on Y, C, F, X and E.

Advantages of reduced fertilizer use rates. Many of the expected advantages of reduced fertilizer use rates are fairly evident. Reduced fertilizer use lowers environmental costs (E) and decreases on-site near-term economic costs per unit of land area (C) (although not necessarily per unit of production). Future reductions in fertilizer use rates may be needed to compensate for increases in fertilizer prices.

Disadvantages of reduced fertilizer use rates. The disadvantages of reducing fertilizer use rates are more subtle. They begin with the possibility of a decline in near-term and longer-term system productivity (Y, F), leading to likely expansions in cropped area (X), with associated environmental costs in the form of accelerated land degradation and biodiversity loss (E), increased prices of food for poor consumers (X), and slower alleviation of poverty (X).

It is not obvious, when the sums are made and the trade-offs assessed, that reduced fertilizer use typically will increase total productivity or, as a consequence, that it usually will foster sustainability.

Moreover, in order to make these sums and assess these trade-offs considerable information is needed on environmental costs, off-site economic costs and longer-term on-site economic costs for alternative land management systems. Just as farmers have tended to underinvest in practices that appear to be sustainable, so researchers have tended to underinvest in the information required to confirm whether those practices are, in fact, sustainable.

Setting Research Priorities

The notion of total productivity as a measure of sustainability has direct implications for setting research priorities. Research managers increasingly are faced with the choice of maintaining investments in commodity/disciplinary research or reallocating resources towards natural resources management research. Total productivity, a concept that includes environmental costs as well as economic costs, can help. Productivity and sustainability goals are both advanced when research resources are allocated to activities that are most likely to increase total productivity. Simple in concept, but difficult in deed.

In the absence of information on environmental and economic costs associated with different technologies, research managers can readily make two kinds of mistakes in allocating their resources. They can:

• *ignore* environmental, off-site and longer-term on-site economic costs (when these are actually quite substantial) and focus on technologies with the highest near-term on-site pay-offs, thereby contributing to unsustainability, or

• *overestimate* environmental, off-site and longer-term on-site economic costs (when these are actually fairly small) and forego productivity-enhancing break-throughs that allow reductions in cropped area and less expensive food for poor consumers.

Increasingly, there is simply no substitute for information on environmental and economic impacts of technical alternatives.

Fostering Adoption

It is one thing to determine whether or not a given practice is sustainable. It is something quite different to determine why farmers do or do not adopt that practice. Sustainable techniques that are not attractive to farmers are of limited usefulness.

There is a substantial literature focusing on factors affecting farmer adoption of practices thought to foster resource conservation and sustainability (Anderson and Thampapillai, 1990; David, 1992; Fujisaka, 1993; Lovejoy and Napier, 1986; Minae and Franzel, 1992; Napier, 1991; Nowak, 1992; Seitz and Swanson, 1980; and many others). Much of this literature emphasizes three sets of factors:

• divergence between on-site and off-site costs and benefits (often affected by institutions and policy),

• near-term vs. longer-term costs and benefits and the time value of money, and

• compatibility of new technology with current farming systems, specifically in terms of arming system variability and complexity, and the costs associated with learning about and adapting new technology.

Note that all of these factors are featured in estimating total productivity (the third factor falls under near-term on-site economic costs). Thus, there is a link between indicators of sustainability and factors affecting farmer adoption behavior.

Divergence Between On-Site and Off-Site Costs and Benefits

Many of the costs associated with particular agricultural practices are not directly incurred by the farmer. These include environmental costs (e.g., introduction of toxic agricultural chemicals into the environment) and off-site economic cost (e.g., lost productivity in lowland irrigated systems due to soil erosion in the uplands). As a whole, farmers -- often struggling to secure a livelihood under difficult conditions and in a risky economic and agroclimatic environment -- understandably are less concerned with off-site costs than those that impinge directly on their own personal financial resources. Practices that are privately profitable often may be socially unprofitable when off-site costs are included in the calculation. This is the familiar concept of externalities.

When environmental costs and off-site economic costs are important, it may make sense to provide incentives for farmers to adopt resource-conserving practices. In the State of Chiapas in Mexico, for example, soil erosion from hillside maize fields has been a major cause of reduced water quality down-stream, affecting power generation efficiency as well as fishing enterprises. In parts of this State, hillside farmers in recent years have adopted conservation tillage techniques (no soil movement, no burning of stover, use of stover as a mulch, chemical weed control) after the government provide these farmers subsidized sprayers and herbicides -- accompanied by a ban (enforced by heavy penalties) on brush and stover burning. Often, however, incentive schemes are excessively costly and complex for government institutions to implement (Kaimowitz, 1992). When environmental costs of farming become a major public issue, as is happening in many developed countries, the rights of the general public to a safe environment begin to take precedence over the rights of farmers to impose external costs and farmers may become legally liable for damages imposed on the public (Batie and Diebel, 1990)

Issues of land tenure form a special kind of divergence between on- and off-site costs and benefits -- in the sense that a farmer's resource base can be thought of as a "site". When land tenure is insecure and when pay-offs to an investment are earned over an extensive period of time, the farmer faces the risk (at times the certainty!) of making an investment that primarily will be for the benefit of others. Farmers understandably avoid this kind of investment. For example, lack of secure access to land has hindered farmer adoption of green manure/cover crop technology in parts of Atlantic Honduras (Buckles *et al.*, 1992).

Often, policy change is needed to reduce a divergence between on-site and off-site costs and benefits. At the very least, those policies can be modified that actively foster land degrading practices, e.g., base acreage policies in the US that hinder farmer adoption of diversified cropping patterns (Faeth *et al.*, 1991) or electricity and water pricing policies in India that foster depletion of limited groundwater resources (Harrington *et al.*, 1992). Policy change that strengthens land tenure can also foster farmer adoption of resource-conserving practices.

Near-Term vs. Longer-Term Costs and Benefits, and the Time Value of Money

Farmers may be reluctant to adopt resource-conserving practices even when off-site costs and benefits are ignored. This is because the costs associated with resource-conserving practices typically are incurred in the near-term, whereas the corresponding benefits are usually earned somewhat later. In order to make near-term and longer-term costs and benefits comparable, economists use the concept of time value of money, implemented through discounting.

It is commonly known that current income is more highly valued than future income, for two reasons:

- current income can be invested, leading to a future income higher than would otherwise be the case;
- current consumption is preferred to future consumption, especially for individuals at the margin of subsistence.

When future cost and benefit streams are discounted back to present values, alternative technologies (with distinct cost and benefit streams) can be compared. The interest rate used for discounting these streams to current values, however, can have a strong effect on the relative attractiveness of different technical alternatives. Resource-poor farmers concerned about current subsistence and the near-term security of their livelihoods (and often with relatively poor access to low-interest credit) typically confront high discount rates. This reduces their ability to make investments with long-term pay-offs.

A hypothetical example is provided in Figure 2 of the effect of discounting on net benefits over a 20 year period for a land-conserving technology vs. a convencional technology. Although the land-conserving technology generates considerably higher net benefits over most of the time period in question, the conventional technology generates higher near-term net benefits (partly because the land-conserving practices require substantial investment during the first two years). Because of this, the sum of discounted net benefits is higher for the conventional technology, even at a moderate discount rate.

The processes illustrated in Figure 2 may seem cold and abstract. These same processes are vividly brought to life in an instance described by Cook (1988) for the Dominican Republic. He notes that, "As farms decline in size, farmers are forced to use destructive farming practices... fenake farmers are now plowing old pastures on 100 % slopes in order to plant corn and beans. When interviewed, the women candidly state that they are aware that the land will likely erode to bedrock in three to five years, but they do not have any other place to grow food. After a few years, they will probably migrate to a city".

Widespread farmer adoption of land-conserving techniques is most likely when these techniques feature acceptable levels of near-term benefits. That is,

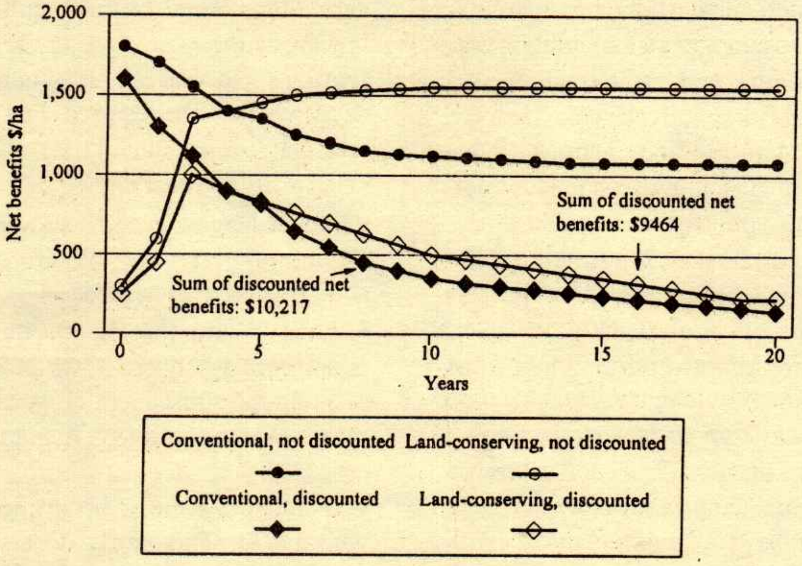

Figure 2. Hypothetical illustration of effects of discounting on streams of costs and benefits for two alternative technologies, using a 12 % annual rate of discount.

technologies should be productivity-increasing as well as resource-conserving. Alternatively, policies can be implemented that reduce discount rates, either by enhancing livelihood security or by making loan funds more readily available to resource-poor farmers.

Farming System Variability and Complexity, and Learning Costs

Productivity-enhancing, resource-conserving technologies at times may be unattractive to farmers even when environmental and off-site costs are ignored, and when near-term benefits are sufficiently high. This may occur when the technology in question is complex, or when it needs substantial adaptation to a wide range of farming systems. In both cases, learning costs for farmers may be so high as to discourage adoption.

Perhaps the best way to illustrate this point is by means of an extended example. The next few paragraphs describe the effect of farming system variability and complexity and farmer learning costs on the adoption of green manure/cover crops in Mexico and Central America. These sections are mainly based on Buckles *et al.* (1992) and Tripp *et al.* (1993).

Maize-legume intercrops and rotations. Land degradation affects several million small-scale hillside farmers in tropical Mexico and Central America. Legume intercrops and rotation systems can help ameliorate many related problems: soil erosion, soil fertility decline, and increased weed incidence. The development and adaptation of these practices currently receive the attention of numerous research and extension institutions. Many of these institutions have studied the use of *Mucuna* spp. for intercropping and rotations with maize.

- When intercropped, *Mucuna* typically is planted between rows of maize 30 days or more after maize seeding and left on the ground as a mulch through which subsequent crops are planted.
- When used in rotation systems, the legume is stick-planted in a cleared field at the beginning of the summer (wet) season. The *Mucuna* develops as a sole crop until November. The abundant growth is then slashed, and a few weeks later winter maize is stick-planted into the mat of decomposing leaves and vines.
- In both intercrop and rotation systems, nutrients are captured and recycled for use by the subsequent food crop, a ground cover is formed to protect the soil, weeds are suppressed, and soil moisture is conserved. Several years are usually required, however, before substantial improvements in resource productivity are realized.

Farming system variability and complexity. Farmers in Mexico and Central America have taken pains to adapt the management of *Mucuna* and other legumes to the immense variability found among farming systems in the region. Much of this adaptation has been influenced by the number of maize crops that can be grown per year, seasonal land and labor availability, and rainfall patterns. Some examples of adaptation are:

• In areas where temperature and rainfall allow two maize crops per year, farmers can choose between legume-winter maize rotations and legume intercropping strategies. Where only rainy season (summer) maize can be grown, fewer options are available.

• In villages with extended late-season rainfall, winter maize planting can be delayed until after *Mucuna* sets seed. Where rainfall drops off more quickly, however, farmers plant winter maize earlier and therefore must reseed *Mucuna* every year (producing *Mucuna* seed on a separate plot). These additional costs slow adoption.

• In Southern Veracruz, farmers will not intercrop *Mucuna* into all of their maize as about one-quarter of the maize area typically is relay-planted with common beans.

• When winter maize is expected to follow summer maize, the legume usually must be intercropped early in the maize season to ensure that biomass production will be adequate to fertilize the subsequent maize crop. This usually increases labor costs for *Mucuna* pruning, necessary to avoid excessive competition with the maize crop.

• The area planted to the legume typically increases as land and labor allocations to other crops decline, the availability of labor resources within the household expands, or off-farm employment becomes less available.

• In villages with limited sources of cash income, *Mucuna*-winter maize rotations are more attractive than legume intercrops in summer maize. This is because growing *Mucuna* during the rainy season frees farm household labor to work off-farm when demand for labor in other communities is at its peak.

Learning costs and farmer training. In general, productivity-enhancing, resource-conserving technologies are complex and require a great deal of site-specific adaptation. In some cases this will require formal training for farmers in new techniques. This does not imply, however, that these new techniques will have been developed by scientists (in the past many have been developed by farmers) or that only better educated farmers will be able to adopt them.

Legume intercrops and rotations usually are intuitively appealing to farmers who have experience with traditional, diversified farming systems. They may seem more complex for farmers accustomed to an agriculture based on monoculture. For most farmers, however, the introduction of legume intercrops or rotations increases the number of management decisions that are required. For example:

• Which legume should be used? *Mucuna* is not always necessarily the best choice.

• Should legume seed be produced or can farmers rely on natural reseeding? Where can seed be obtained if additional seed is needed?

• When should the legume be planted? Should it be intercropped between rows of maize and killed before planting the subsequent crop, or planted within rows of maize and managed as a living mulch in the subsequent crop?

• Should the legume be pruned to avoid competition with maize? This partly depends on the answer to the question on the legume planting date.

• What spacing should be used for legume planting? Note that spacing may vary for particular parts of a field. Areas infested with weeds may be planted with a legume rotation to choke out the weeds over the course of a season while another part of the same field is intercropped with the legume.

• Should the legume be planted on all fields or (if labor is limited) only on selected fields? If only on selected fields, what are good criteria for field selection?

• Does the planting of a legume such as *Mucuna* increase the risk of losing a crop to brush fires? (Note that the presence of dry *Mucuna* mulch may facilitate the spreading of fires). Do the advantages outweigh the extra risk?

In short, effective management of legumes requires many management decisions and different types of knowledge and extension services. Moreover, information requirements are likely to vary over fields within farms, and over time within farms (as legume management systems evolve) as well as over cropping systems.

CONCLUSIONS

It is often claimed that the maintenance of soil productivity is essential to the sustainability of agriculture, and that nutrient cycling within agroecosystems is fundamental to this objective. In addition, many proponents of sustainable agriculture maintain that increased use of external inputs, including fertilizers, is unwise. Scientists concerned with organizing research and extension endeavors for the specific purpose of fostering sustainable agriculture through nutrient cycling or reduced external input use are likely find themselves confronting two sets of awkward and troublesome questions:

1. How can the influence of increased nutrient cycling or reduced input use on the sustainability of agriculture be measured? How can it be ascertained when these practices increase or actually decrease sustainability?

2. What are some of the factors that influence farmer adoption of practices that feature nutrient cycling or reduced external input use, and how can the adoption of these practices be encouraged?

Although the notion of sustainability can be interpreted in terms of agroecology, stewardship or sustainable growth, there is a considerable overlap among these interpretations. One particular definition of sustainable agriculture was emphasized in this paper: **"A sustainable agricultural system is one that can indefinitely meet demands for food and fiber at socially acceptable economic and environmental costs"** (Crosson, 1992). This definition is operationalized through the notion of **total productivity**, the sum of the value of all outputs divided by the sum of the value of all inputs, including near-term on-site economic costs, longer-term on-site economic, off-site economic costs, and environmental costs. Practices that feature nutrient cycling or reduced external inputs will foster sustainability to the extent that they also improve total productivity.

It is one thing to determine whether or not a given practice is sustainable. It is something quite different to determine why farmers do or do not adopt that practice. Sustainable techniques that are not attractive to farmers are of limited usefulness. Adoption has been shown to be affected by at least three sets of factors:

1. Divergence between on-site and off-site costs and benefits (often affected by institutions and policy).

2. Near-term vs. longer-term costs and benefits and the time value of money.

3. Compatibility of new technology with current farming systems, specifically in terms of farming system variability and complexity, and the costs associated with learning about and adapting new technology.

An understanding of these and other economic concepts can help focus research on sustainability themes. Effective natural resources management research must concentrate its efforts on technologies likely to increase (not decrease) sustainability, and on practices that farmers are likely to find attractive. Increasingly, there is simply no substitute for information on environmental and economic impacts of technical alternatives, and on the factors that affect farmer adoption of productivity-enhancing, resource-conserving technology.

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INTERPRETACION ECONOMETRICA DE LOS EXPERIMENTOS CON FERTILIZANTES

Econometric Interpretation of Fertilizer Experiments

Angel Martínez Garza[1] y Miguel Angel Martínez Damián

RESUMEN

Si bien los experimentos con fertilizantes se proyectan con frecuencia defectuosamente, es todavía más frecuente encontrar deficiencias en la interpretación económica de sus resultados. De aquí, el propósito de este trabajo es discutir, en forma breve, algunos aspectos económicos del análisis de esta clase de experimentos. Se parte del concepto ingreso neto por unidad experimental, tratándose como una variable aleatoria similar a los rendimientos de campo. Se hace énfasis en los experimentos de fuentes de un nutrimento, de dosis de fertilizantes y en la estimación de las dosis óptimas económicas.

Palabras clave: Interpretación econométrica, optimización, experimentos de fertilizantes.

SUMMARY

Although fertilizer experiments are often defectively designed, it is more frequent to find deficiencies in the economic interpretation of results. Hence, it is the purpose of this paper to discuss briefly, some economical aspects of the analysis of this kind of experiments. The discussion is based on the concept of net income per experimental unit, treating it as a random variable as is done with field yields. Emphasis is placed on the experiments designed to study sources of a nutrient, doses of fertilizers and the estimation of optimal economical dosage.

Index words: Econometric interpretation, optimization, fertilizer experiments.

INTRODUCCION

Considérese un proceso productivo en el cual un empresario utiliza k insumos variables y uno o más insumos fijos con el fin de producir un solo producto. Su función de producción, de acuerdo con Henderson y Quandt (1958), establece la cantidad de su producto (q) como una función de las cantidades de sus insumos variables ($x_1, x_2, ..., x_k$):

$$q = f(x_1, x_2, ..., x_k) \qquad (1)$$

donde (*1*) se supone que es una función continua univalorada, con derivadas parciales continuas de primero y segundo orden, definiéndose solamente para valores no negativos de los niveles de los insumos y del producto. Además, la función de producción se construye bajo la hipótesis de que los insumos fijos ocurren a niveles predeterminados, los cuales no puede alterar el empresario durante el mismo período de producción. El ingreso total de un empresario que vende su producto en un mercado perfectamente competitivo, es dado por el número de unidades que vende multiplicado por el precio unitario fijo (p) que recibe. Su ganancia o ingreso neto (π) es la diferencia entre su ingreso total y su costo total de producción (c):

$$\pi = pq - c. \qquad (2)$$

Sustituyendo $q = f(x_1, x_2,..., x_k)$ y $c = r_1x_1+r_2x_2+...+r_kx_k+b$, donde r_i, $i = 1, 2,..., k$, es el costo unitario del i-ésimo insumo y b es el costo fijo de producción, se obtiene:

$$\pi = pf(x_1, x_2, ..., x_k) - r_1x_1 - r_2x_2 - ... - r_px_k - b \qquad (3)$$

Es decir, el ingreso neto es una función de los niveles de los insumos. El empresario tiene la libertad de hacer variar los niveles de los insumos, variando consecuentemente el nivel del producto, y su último objetivo en la asignación de recursos es lograr maximizar sus ganancias. Puede demostrarse, véase

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Martínez y Martínez (1992), que π es un máximo cuando:

$$\frac{\partial \pi}{\partial x_i} = p\frac{\partial f}{\partial x_i} - r_i = o, i = 1,2,\ldots,k. \quad (4)$$

Trasladado el problema a la agricultura y, en particular, a los estudios de fertilidad de los suelos, *f* es la función de respuesta que expresa la producción de un cultivo, como una función de las dosis de los nutrimentos. Los nutrimentos nitrógeno, fósforo, potasio, fierro, etc., son los insumos del proceso productivo; el empresario es, obviamente, el propio agricultor.

EXPERIMENTACION CON FERTILIZANTES

La metodología básica relativa al uso económico de los fertilizantes, es descrita por Munson y Doll (1959) con cierta extensión. Las ideas son sencillas y son válidas en cualquier momento; si algo ha cambiado a través del tiempo, no han sido los conceptos, sino los métodos experimentales. En términos concretos, la metodología se resume en los siguientes puntos:

1. Se proyecta de preferencia una serie de experimentos factoriales que comprendan diversas fórmulas de fertilización, con el diseño de los tratamientos más conveniente a juicio del investigador.
2. Las deficiencias nutrimentales se reflejarán obviamente en los rendimientos observados. Así, el rendimiento se aproxima en términos de una función *f* de los niveles de los insumos, la cual puede ser un polinomio de grado entero o fraccionario, una función exponencial o potencial, etc., que refleje tanto como sea posible, la ley de rendimientos decrecientes.
3. Se obtienen, por los métodos matemáticos apropiados, las dosis de los nutrimentos que producen al agricultor el máximo ingreso neto por hectárea.

Diseño de los Experimentos

Los diseños experimentales más apropiados para las investigaciones con fertilizantes son los factoriales simétricos y asimétricos, los cuales se describen con cierta extensión en Martínez (1988), y los factoriales incompletos cuyo diseño básico proviene de las ideas de Box y Wilson (1951), Finney (1945) y Plackett y Burman (1946). De estos últimos, algunas fracciones de factoriales se han empleado en investigaciones agrícolas pero no con mucha frecuencia. Posiblemente los **diseños compuestos centrales** de Box y Wilson fueron los diseños que más frecuentemente se hayan empleado en estudios con fertilizantes. Lo cierto es, sin embargo, que inspirados en las aportaciones mencionadas, los investigadores conectados con la agricultura han sugerido diseños de tratamientos específicos, como el diseño San Cristóbal (Rojas, 1962), el diseño San Cristóbal ortogonalizado (Rojas, 1971), los cuadrados y cubos dobles (Martínez, 1990), o los diseños Plan Puebla (Turrent y Laird, 1975).

Los nombres aplicados a los diseños anteriores son locales en el sentido de que así se llaman en México, en otras partes del mundo raras veces se les aplica a estos diseños un nombre especial.

Análisis de los Experimentos

Los experimentos se analizan combinando la técnica del análisis de varianza del diseño geométrico básico (bloques completos al azar, cuadro latino, etc.), con los métodos de regresión múltiple estándar, o bien, con los métodos de regresión no lineal programados en paquetes computacionales estadísticos como SAS (SAS Institute, 1989). Obsérvese que la técnica no se dirige a separar el tratamiento o la fórmula de fertilización que mejor se comporta en campo o económicamente, porque se pierden las ventajas que ofrece la estructura factorial, al estimar los efectos del modelo ajustado combinando los efectos parciales de todas las combinaciones de tratamientos. Consecuentemente, la variación atribuible a tratamientos en el análisis del experimento, o de la serie de experimentos, se parte en dos componentes como se indica en el Cuadro 1.

El modelo de regresión ajustado se acepta como bueno, si la regresión es significativa y las desviaciones de regresión no lo son. La significancia de ambos componentes se prueba comparando los cuadrados medios correspondientes con el cuadrado medio del error.

Obsérvese que puede ocurrir que varios modelos de regresión sean significativos, sin embargo, el investigador debe elegir de todos ellos, el más compacto (con menos términos) y más significativo. Este es el principio de **parsimonia** advocado por Box y Jenkins (1970).

Cuadro 1. Partición de tratamientos en el análisis de varianza de un experimento de fertilizantes.

Fuentes de variación	Grados de libertad	Suma de cuadrados	Cuadrados medios
Tratamientos	t-1	†$SCT = \frac{\sum_{i=1}^{t} T_i^2}{r} - C$	CMT
Regresión	q	SCReg	CMReg
Desviaciones de regresión	t-1-q	SC(Desv. reg)	CM(Desv. reg.)
Error	η	SCE	CME

† T_i = Total del tratamiento i; C = Factor de corrección = (gran total)^2/N; N = Número total de observaciones; r = Número de repeticiones de los tratamientos.

Como un ejemplo, considérese la serie de cinco experimentos sobre caña de azúcar con el diseño San Cristóbal que reportan Martínez y Martínez (1992). El análisis de varianza combinado, junto con la partición de tratamientos que se obtiene al ajustar el modelo:

$$y_i = \beta_O + \beta_I N_i + \beta_{II} N^2_i + \beta_2 P_i + \varepsilon_i,\ i=1,2,\ldots,n,$$

se da en el Cuadro 2. Las combinaciones de tratamientos fueron fórmulas de los tres nutrimentos mayores: nitrógeno, fósforo y potasio, aplicados en dosis de 0 a 300 kg ha^{-1} de cada nutrimento.

La ecuación de regresión estimada, cuando el rendimiento $\hat{y}$, se expresa en toneladas de caña por hectárea, se reduce a la forma:

$$\hat{y} = 71.4368 + 0.110675N - 0.0002023N^2 + 0.0412P \qquad (5)$$

Obsérvese que N y P no interaccionan y que el efecto de P es lineal; de aquí, la interpretación económica puede hacerse en forma independiente para cada nutrimento. Así, para nitrógeno la Condición 4 implica,

$$\frac{\partial \hat{y}}{\partial N} = 0.110675 - 0.0004046N = \frac{P_N}{P_y}, \qquad (6)$$

donde P_N y P_y son, respectivamente, el costo del kilogramo de nitrógeno aplicado al suelo por hectárea y el precio de liquidación al agricultor por tonelada de caña. De la Ecuación 6 la dosis óptima de nitrógeno N^*, es dada por:

$$N^* = \frac{0.110675 - P_N / P_y}{0.0004046} \qquad (7)$$

Las aplicaciones de fósforo, por otra parte, serán económicas, si $0.0412P_y > P_P$ donde P_P es el costo de aplicar un kilogramo de fósforo por hectárea. Nótese que $0.0412P_y$ es el ingreso por hectárea que produce una dosis de 1 kg ha^{-1} de fósforo, en tanto que P_P es lo que se invierte para lograr tal ingreso; consecuentemente, el ingreso neto resultaría positivo con la condición anterior, lo que demostraría la conveniencia de aplicar este nutrimento.

Nótese, también, que en el proceso anterior de optimación, no se buscó la fórmula de fertilización, de aquellas ensayadas, que produjo el mayor ingreso neto. Esto puede hacerse, pero desde el punto de vista de los autores no es la técnica apropiada para establecer una recomendación. Esta técnica se usa con frecuencia, pero resulta ser inapropiada (se ilustrará enseguida la manera correcta de aplicarla, en el entendido de que las conclusiones sólo deben servir para orientar al investigador en su recomendación final).

Análisis Estadístico de los Ingresos Netos

Si se han analizado los datos de rendimiento de campo para analizar el ingreso neto, es innecesario obtener los ingresos netos por parcela experimental, puesto que éstos pueden derivarse del análisis del rendimiento de campo. Por ejemplo, para la serie de experimentos sobre fertilizantes en caña de azúcar que ha ilustrado la discusión, los rendimientos promedio de caña, $\bar{y}_i$, en t ha^{-1}, se dan en el Cuadro 3, Columna 1.

Cuadro 2. Análisis de varianza combinado de cinco experimentos. Rendimiento de caña (t ha^{-1}).

Fuentes de variación	Grados de libertad	Suma de cuadrados	Cuadrados medios	F calculada
Experimento	4	64475.11	16118.78	93.64**
Reps. dentro exp.	15	6277.17	418.47	2.43**
Tratamientos	11	15200.78	1381.89	8.03**
Regresión	3	13315.33	4438.44	25.78**
Desv. de regr.	8	1885.44	235.00	1.37
Trat. x Exp.	44	11659.94	265.00	1.54
Error combinado	165	28402.81	172.14 $\equiv s^2$	
Total	239	126015.81		

* Significancia a 1 %.

Cuadro 3. Cálculo de ingresos netos. Experimentos de fertilizantes.

i	Tratamientos N	P	K	(r) Rendimiento medio	(2) Costo variable	(3) Ingreso total	(4) Ingreso neto
	- - - - kg ha^{-1}		- - - -	t ha^{-1}	- - - - - - - - - - - - -	\$ ha^{-1}	- - - - - - - - - - - - -
1	0	0	0	72.4833	0	14496.67	14496.67
2	200	0	0	83.1917	800	16638.33	15838.33
3	0	200	0	80.3417	700	16068.33	15368.33
4	200	200	0	93.2833	1500	18656.67	17156.67
5	0	0	200	72.4250	500	14485.00	13985.00
6	200	0	200	84.7083	1300	16941.67	15641.67
7	0	200	200	74.4583	1200	14891.67	13691.67
8	200	200	200	89.6500	2000	17930.00	15930.00
9	100	100	100	83.8000	1000	16760.00	15760.00
10	300	100	100	93.0667	1800	18613.33	16813.33
11	100	300	100	96.8583	1700	19371.67	17671.67*
12	100	100	100	88.9417	1500	17788.33	16288.33
DSH							2711.97

* Superior significativamente al testigo (0-0-0).

De aquí, si se consideran los precios unitarios P_y = *\$ 200*, P_N = *\$ 4*, P_P = *\$ 3.5* y P_K = *\$ 2.5*, entonces el ingreso neto por hectárea (más el costo fijo de producción), debido al *ié*simo tratamiento, $\bar{I}_i$, es dado por:

$$\bar{I}_i = P_y\bar{y}_i - P_N N_i - P_P P_i - P_K K_i, i = 1,2,\ldots,12 \quad (8)$$

donde N_i, P_i y K_i son las dosis por hectárea de nitrógeno, fósforo y potasio, debidos a la fórm ula *i* de fertilización. De aquí, la contribución de un ingreso neto medio a la varianza estimada de cualquier contraste entre medias de ingreso netos es:

$$\widehat{VAR}(\bar{I}) = P_y^2 x \widehat{VAR}(\bar{R}) = P_y^2 x \frac{s^2}{r} = \frac{200^2 x 172.14}{20}$$

donde r= 20, es el número total de repeticiones de cada tratamiento, puesto que cada experimento comprende cuatro bloques completos y son cinco experimentos en total. Por consiguiente, para comparar los ingresos netos medios por el método de Tukey, tiene que calcularse la estadística:

$$DSH = q_{\alpha;12,\eta}\sqrt{\widehat{VAR}(\bar{I})},$$

donde α es el nivel de significancia que se elige, η son los grados de libertad del error combinado y 12 es el número de medias que se comparan. Tomando $\alpha = 0.05$, y puesto que $\eta = 165$ grados de libertad, los del término de error combinado, entonces:

$$DSH = 4.622\sqrt{\frac{40000x172.14}{20}} = 2711.97\,.$$

El cálculo de los ingresos netos por tratamiento se muestra en el Cuadro 3, el cual permite seleccionar al

Tratamiento 11, fórmula 100-300-100, como el único que supera significativamente al testigo absoluto, fórmula 0-0-0. El lector debe observar, sin embargo, que este análisis ignora los efectos particulares de los nutrimentos y las tendencias que sólo puede descubrir la técnica de regresión múltiple, al combinar simultáneamente la información producida por todos los tratamientos. Un análisis simple de la información experimental puede establecer fácilmente el efecto nulo del potasio, siendo riesgoso recomendar la combinación 100-300-100.

Los investigadores del área de fertilidad de suelos ignoran que el ingreso neto es una variable aleatoria, y no realizan pruebas estadísticas para seleccionar el tratamiento que produce el mayor ingreso. Su interpretación económica se limita a comparar los ingresos netos medios de los tratamientos, sin observar si realmente las diferencias entre ellos son estadísticamente significativas.

Recomendación Final

Con los precios unitarios considerados, la Fórmula 4 produce como dosis óptima de nitrógeno:

$$N^* = \frac{0.110675 - 4/100}{0.0004046} = 224 \text{ kg / ha.}$$

Con relación al fósforo $0.0412P_y = 0.412x200 = \$\ 8.24$ es estrictamente mayor que $P_P = \$\ 3.5$, siendo económico aplicarlo, puesto que dejan una ganancia positiva, las adiciones de este nutrimento. Además, siendo lineal su efecto, como lo muestra la relación 4, puede recomendarse cualquier dosis de fósforo entre 0 y 300 kg ha^{-1}. Myers (1971) cubre en detalle tanto las técnicas de diseño como de análisis, de los experimentos que se dirigen a estimar una función de respuesta en términos de los niveles de varios factores. El énfasis en Myers es sobre experimentación industrial donde se busca optimar una respuesta, situación que ocurre en la agricultura.

Observación Importante

El análisis de los ingresos netos, al estilo descrito, es más importante en aquellos experimentos de fertilizantes cuyos tratamientos no presentan una estructura factorial, como por ejemplo en el caso en que se consideran diversas fuentes de un nutrimento en particular, digamos nitrógeno. Las fuentes de nitrógeno pueden ser, por ejemplo: urea, sulfato de amonio, nitrato de amonio y uno o más tratamientos testigo. Se fija el nitrógeno al nivel definido por el investigador, con aplicaciones de fósforo y potasio fijas a niveles predeterminados. Supóngase, por ejemplo, que para un cultivo de caña de azúcar se propone comparar el efecto de los tratamientos:

1. Testigo absoluto (0-0-0).
2. Testigo en P y K (0-100-50).
3. Fórmula (150-100-50), nitrógeno en forma de urea.
4. Fórmula (150-100-50), nitrógeno en forma de nitrato de amonio.
5. Fórmula (150-100-50), nitrógeno en forma de sulfato de amonio.

Alojado el experimento en r bloques completos al azar, el análisis de varianza de los rendimientos de campo, conduciría a la estadística de Tukey para separar medias:

$$DSH_y = q_{\alpha;5,\eta} \sqrt{\frac{S^2}{r}}, \qquad (9)$$

donde q es el valor tabulado del rango estandarizado al nivel α de significancia, para cinco medias que se comparan y para $\eta = 4(r-1)$ grados de libertad del error experimental. Para el análisis de los ingresos netos, el investigador debería establecer los costos por unidad de superficie distintos de los costos fijos de producción, para cada tratamiento. Sean C_1, C_2, C_3, C_4 y C_5 los costos respectivos de aplicar los tratamientos 1 a 5, y sea $\bar{y}_i$, el rendimiento medio atribuible al tratamiento i, entonces $\bar{I}_i$, el ingreso neto (más el costo fijo de producción), atribuible al tratamiento i, es dado por:

$$\bar{I}_i = P_y \bar{y}_i - C_i, \ i = 1,2,\ldots,5, \qquad (10)$$

donde P_y es el precio de venta de la tonelada de caña. Considerados los costos C_i como variables fijas, la contribución a la varianza de un constraste entre ingresos netos $\bar{I}_i$, de una media particular sería:

$$\widehat{VAR}(\bar{I}) = P_y^2 \widehat{VAR}(\bar{y}) = \frac{P_y^2 S^2}{r}, \quad (11)$$

de modo que la estadística de Tukey para la comparación de los ingresos netos medios, sería:

$$DSH_I = q_{a;5,\eta} \sqrt{\frac{P_y^2 S^2}{r}} = P_y q_{a;5,\eta} \sqrt{\frac{S^2}{r}}$$

de donde:

$$DSH_I = P_y (DSH_y) \quad (12)$$

Obviamente se ve innecesario hacer el análisis estadístico de los ingresos netos, porque la estadística de Tukey para la comparación de los ingresos netos puede escribirse como en la Ecuación 12 donde DSH_y es la estadística de Tukey para la separación estadística de las medias de rendimiento.

ANALISIS PARCIAL DE LOS EXPERIMENTOS

Los diseños de tratamientos que se emplean en los estudios de fertilidad de suelos, como los diseños San Cristóbal, los cuadrados y cubos dobles, los diseños Plan Puebla, etc., tienen una particularidad en común; emplean como base un factorial 2^k. Así, por ejemplo, el diseño San Cristóbal para tres factores comprende un factorial 2^3 como diseño básico. Es muy conveniente siempre analizar en forma preliminar al factorial, utilizando sus resultados para afinar el análisis del experimento completo; en el caso del San Cristóbal, el factorial 2^3 constituye las dos terceras partes del experimento, su análisis debe detectar muy probablemente los efectos más significativos. Considérese el experimento con el diseño San Cristóbal que emplea Martínez (1988, página 399) para ilustrar el método de análisis de tales experimentos. Las primeras ocho combinaciones de tratamientos constituyen un factorial 2^3, cuyo análisis estadístico detecta al efecto principal del nitrógeno, como el único efecto altamente significativo sobre el rendimiento de campo de la caña de azúcar (significancia a 1 %), en tanto que el fósforo y la interacción NK muestran significancia a 5 %; la interacción NP es casi significativa a 5 %. Ahora, como el potasio ha sido un elemento raras veces deficiente en los suelos cañeros, puede concluirse de este examen preliminar del experimento, que el nitrógeno y el fósforo deben ser los principales responsables de las variaciones en el rendimiento de campo. Al considerar el experimento completo, se ajusta un modelo cuadrático en los niveles de nitrógeno y fósforo, obteniéndose el análisis de varianza del Cuadro 4. Nótese que al ajustar el modelo cuadrático en nitrógeno y fósforo, lo que se desvía la regresión con respecto a tratamientos, con seis grados de libertad, no es variación significativa, lo que comprueba que el potasio no afectó al rendimiento de campo. El modelo de regresión ajustado es:

$$\hat{y} = 75.6125 + 0.31609N + 0.10137P - 0.00042546N^2 - 0.00016799P^2 - 0.00030006NP.$$

El análisis económico detecta que las adiciones de fósforo no incrementan el ingreso neto, siendo el nitrógeno el único nutrimento que produce incrementos significativos en el propio ingreso neto.

El lector puede recurrir a los métodos de optimación descritos en Martínez y Martínez (1992), para realizar la interpretación económica de los resultados experimentales. Los autores mencionados ilustran el uso de los métodos microeconómicos que se mencionan en la INTRODUCCION de este trabajo. Para el problema presente, la técnica del análisis canónico puede localizar la combinación (N, P) que produce el máximo ingreso neto por hectárea. Véase la referencia citada.

EXPERIMENTO DE FERTILIZANTES CON CULTIVOS SEMIPERENNES

Con cultivos semiperennes como la caña de azúcar, en los cuales cada unidad experimental produce dos o más cosechas, la definición de la dosis óptima económica puede basarse en el concepto del ingreso actual. Supóngase, por ejemplo, que en plantilla un cultivo de caña estima el rendimiento de caña en términos de la ecuación de regresión:

$$\hat{y}_1 = \hat{\alpha}_0 + \hat{\alpha}_1 N + \hat{\alpha}_2 N^2,$$

en tanto que en soca el rendimiento de caña se estima por:

$$\hat{y}_2 = \hat{\beta}_O + \hat{\beta}_1 N + \hat{\beta}_2 N^2.$$

Si en plantilla cada tonelada de caña se liquida al agricultor, a razón de P_1 pesos, en tanto que en soca, cada tonelada de caña se le paga a razón de P_2 pesos, y si en plantilla cada kilogramo por hectárea de nitrógeno requiere una inversión de P_{N1} pesos, en tanto que en soca se invierten P_{N2} pesos por cada kilogramo por hectárea de nitrógeno que se aplica, entonces los ingresos netos obtenidos por el agricultor, serían, denotando por C_{oi} los costos fijos en la zafra i:

$$I_1 = P_1\hat{y}_1 - C_{O1} - P_{N1}N = P_1\hat{\alpha}_O + P_1\hat{\alpha}_1 N^2 - C_{O1} - P_{N1}N,$$

$$I_2 = P_2\hat{y}_2 - C_{O2} - P_{N2}N = P_2\hat{\beta}_O + P_2\hat{\beta}_1 N + P_2\hat{\beta}_2 N^2 - C_{O2} - P_{N2}N.$$

El ingreso neto total no puede ser la suma de I_1 con I_2 porque un peso que se gane en soca, no es equivalente a un peso que se gane en plantilla. Impuesto el capital a una razón de interés i, un peso dentro de un año, es equivalente actualmente a $1/(1+i)$ pesos. En consecuencia, en términos de valor actual, los ingresos de las dos cosechas suman:

$$I = I_1 + I_2/(I+i) = [P_1\hat{\alpha}_O - C_{O1} + P_2\hat{\beta}_O/(I+i) - C_{O2}/(I+i)] + [P_1\hat{\alpha}_1 + P_2\hat{\beta}_1/(I+i) - P_{N1} - P_{N2}/(I+i)]N + [P_1\hat{\alpha}_2 + P_2\hat{\beta}_2/(I+i)]N^2.$$

Hágase:

$$P_1\hat{\alpha}_O - C_{O1} + P_2\hat{\beta}_O/(I+i) - C_{O2}/(I+i) = A_O,$$

$$P_1\hat{\alpha}_1 + P_2\hat{\beta}_1/(I+i) - P_{N1} - P_{N2}/(I+i) = A_1,$$

y

$$P_1\hat{\alpha}_2 + P_2\hat{\beta}_2/(I+i) = A_2.$$

I, será un máximo, si $dI/dN = A_1 + 2A_2N = o$ siempre que $d^2I/dN^2 < o$. Nótese que se asume la separabilidad de los ingresos netos en plantilla y soca, con respecto al ingreso neto total I. Consecuentemente, la dosis de nitrógeno que maximiza el ingreso actual, es:

$$N^* = -\frac{A_1}{2A_2},$$

siempre que $A_2 < o$.

No se ven muchas complicaciones, excepto por expresiones algebráicas voluminosas, cuando la función de respuesta del cultivo en cada cosecha sea un polinomio cuadrático en dos o más factores, o cuando la función de respuesta adopte formas matemáticas más complicadas. El método que aquí se propone para localizar el nivel óptimo económico en estudios de fertilizantes sobre cultivos perennes, puede extenderse con facilidad a situaciones más complicadas que la descrita.

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