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Productivitat de cultius extensius i fertilitat i qualitat de sòls associades a les aplicacions de dejeccions ramaderes en un sistema agrari mediterrani

Francesc Domingo Olivé

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UNIVERSITAT DE LLEIDA

DEPARTAMENT DE MEDI AMBIENT I CIÈNCIES DEL SÒL

Programa de doctorat:

CIÈNCIES DEL SÒL: GÈNESI, ÚS I CONSERVACIÓ DE SÒLS

Productivitat de cultius extensius i fertilitat i qualitat de sòls associades a les aplicacions de dejeccions ramaderes en un sistema agrari mediterrani

Francesc Domingo Olivé

Tesi dirigida per:

Dra. Àngela D. Bosch Serra i Dra. M. Rosa Yagüe Carrasco

Lleida, Gener de 2016

Memòria presentada per Francesc Domingo Olivé en satisfacció dels requisits necessaris per optar al grau de doctor.

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Ciències del Sòl: Gènesi, ús i conservació de sòls

Directores:

Dra. Àngela D. Bosch Serra

Dra. M. Rosa Yagüe Carrasco

Lleida, Gener de 2016

AGRAÏMENTS

El camí que m'ha portat fins aquí no és curt. Fa vint anys que vaig començar els estudis de doctorat. En un període de temps d'aquestes dimensions, com és lògic, han passat moltes coses. I en els treballs realitzats hi han estat involucrades, d'una o altra manera, un munt de persones. Això vol dir que la llista d'agraïments a fer és llarga i el risc de no esmentar algú que s'ho mereix és elevat. Intentaré que els descuits siguin mínims i demano disculpes d'avançada per les omissions, que us asseguro que no són voluntàries.

El Jaume Boixadera, referent en tantes coses, em va introduir en la necessitat de l'estudi de la contribució de les dejeccions ramaderes a la fertilització dels cultius. I va actuar i col·laborar de forma decidida i decisiva en l'inici dels treballs. I ho ha continuat fent, amb molta paciència i capacitat de perdonar les errades, durant tot aquest temps. Mai li podré agrair prou.

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Els coautors dels articles que s'inclouen han estat claus per poder realitzar tot el treball que es mostra. Sense la seva ajuda no hauria estat possible obtenir tota aquesta informació i interpretar-la adequadament.

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RESUM

La fertilització de cultius extensius amb dejeccions ramaderes és una pràctica freqüent i molt estesa, especialment en àrees amb una elevada cabanya ramadera, com és el cas de moltes zones dels sistemes agrícoles de secà i regadiu de Catalunya i Aragó. En els fems i els purins, els nutrients estan lligats en part a la matèria orgànica i no estan completament disponibles durant el cicle de cultiu en el que s'apliquen. D'altra banda, el carboni orgànic que aporten pot modificar les característiques físiques i químiques del sòl. Ambdós aspectes, l'efecte sobre els cultius i sobre el sòl, és necessari estudiar-los a llarg termini. Es presenten els efectes de l'aplicació de fems de boví i purins de porcí durant un periode llarg (7-12 anys) de temps sobre el rendiment de blat de moro en regadiu i cereal d'hivern en secà, la qualitat del gra i la utilització del nitrogen (N). Per obtenir produccions elevades de blat de moro (prop de 15 Mg ha^{-1}) cal combinar aplicacions de fems de boví en fons (30 Mg ha^{-1}) amb aportacions de N mineral (150-200 kg N ha^{-1}) en cobertora. Aportacions de dosis superiors de fems de boví o de N mineral no comporten una major producció, acumulen N mineral en el sòl augmentant el risc de pèrdues i redueixen l'eficiència en el ús del N. Pels cultius de blat i ordi aportar dosis de purins properes a les permeses, abans de la sembra, durant un període de dotze anys, contribueix a augmentar les produccions de cereal d'hivern i el contingut en proteïna del gra. Complementar aquestes aportacions amb N mineral en cobertora també augmenta la producció de gra i el contingut en proteïna, però tendeix a disminuir la densitat i el pes del gra de blat i ordi. Les aportacions anuals de fems de boví, durant onze anys, augmenten l'estabilitat dels agregats del sòl en front de processos de desestabilització provocats per la pluja o el reg, tant en reg com en secà, millorant la protecció del sòl en front de la degradació. En el cas de l'aplicació de purins, s'observa una tendència a la millora de l'estabilitat dels agregats menys marcada. També augmenta el contingut en carboni orgànic del sòl respecte l'ús de fertilitzants minerals. Aquest increment s'observa especialment en la fracció lleugera de la matèria orgànica del sòl, independentment de si és secà o regadiu. S'observa una relació lineal positiva significativa entre aquest paràmetre i l'estabilitat dels agregats del sòl. El contingut en carboni orgànic de la fracció de matèria orgànica entre 0,05 i 0,2 mm pot ser un bon indicador de la qualitat del sòl en relació a les pràctiques de fertilització. Les aplicacions mencionades també provoquen un augment de porus de mida mitjana-gran (>65 µm), que comporta una major infiltració de l'aigua de pluja o reg, evitant escolament, i una major permeabilitat del sòl. Es produeix, també, un increment de l'abundància de cucs de terra encara que no s'ha trobat cap relació entre aquests dos paràmetres.

RESUMEN

La fertilización de cultivos extensivos con deyecciones ganaderas es una práctica frecuente y muy extendida, especialmente en áreas con una elevada cabaña ganadera, como la existente en muchas zonas de los sistemas agrícolas de secano y regadío de Catalunya y Aragón. En los estiércoles y purines, los nutrientes están ligados en parte a la materia orgánica y no están completamente disponibles durante el ciclo de cultivo en el que se aplican. Por otra parte, el carbono orgánico que aportan puede modificar las características físico-químicas del suelo. Ambos aspectos, el efecto sobre los cultivos y sobre el suelo, es necesario estudiarlos a largo plazo. Se presentan los efectos de la aplicación de estiércoles de bovino y purines de porcino durante un periodo largo (7-12 años) de tiempo sobre el rendimiento de maíz en regadío y cereal de invierno en secano, la calidad del grano y la utilización del nitrógeno (N). Para obtener producciones elevadas de maíz (cerca de 15 Mg ha^{-1}) es necesario combinar aplicaciones de estiércol de bovino en fondo (30 Mg ha^{-1}) con aportaciones de N mineral (150-200 kg N ha^{-1}) en cobertera. Aportes de dosis superiores de estiércol de bovino o de N mineral no comportan una mayor producción, acumulan N mineral en el suelo aumentando el riesgo de pérdidas y reducen la eficiencia en el uso del N. Para trigo y cebada, aportar dosis de purines cercanas a las máximas permitidas, antes de la siembra, durante un periodo de doce años, contribuye a aumentar las producciones de cereal de invierno y el contenido en proteína del grano. Complementar estas aportaciones con N mineral en cobertera también aumenta la producción de grano y el contenido en proteína, pero tiende a disminuir la densidad y el peso del grano. Las aportaciones anuales de estiércol bovino, durante once años, aumentan la estabilidad de los agregados del suelo frente a los procesos de desestabilización por parte de la lluvia o el riego, tanto bajo riego como en secano, mejorando la protección del suelo frente a la degradación. En el caso de la aplicación de purines, se observa una tendencia a la mejora de la estabilidad de los agregados más tenue. También aumenta el contenido en carbono orgánico del suelo respecto el uso de fertilizantes minerales. Este incremento se observa especialmente en la fracción ligera de la materia orgánica del suelo, con independencia de la existencia o no de riego. Se observa una relación lineal positiva significativa entre este parámetro y la estabilidad de los agregados del suelo. El contenido en carbono orgánico de la fracción de materia orgánica entre 0,05 y 0,2 mm puede ser un buen indicador de la calidad del suelo en relación a las prácticas de fertilización. Las aplicaciones mencionadas también provocan un aumento de poros de tamaño mediano-grande (>65 µm), que comporta una mayor infiltración del agua de lluvia o riego, evitando escorrentía, y una mayor permeabilidad del suelo. A lo anterior se añade un incremento de la abundancia de lombrices de tierra aunque no se ha encontrado ninguna relación entre estos dos parámetros.

SUMMARY

Arable crop fertilization using manure or slurry is a common practice in areas with a high livestock density like many in the agricultural, rainfed and irrigated, systems of Catalonia and Aragon. Nutrients in manure and slurries are partly linked to organic matter and they are not completely available for the crops during the growing season when they are applied. In the other hand, the organic carbon applied may modify some soil physic-chemical characteristics. Both, the effects on crop and on soil, need to be studied by carrying out long-term trials. We present some results on the effects of manure and slurry application during a long period (7-12 years) on irrigated maize and rainfed winter cereals yield, grain quality and use of nitrogen (N). To achieve high irrigated maize yields (around 15 Mg ha^{-1}) it is necessary to complement presowing dairy cattle manure applications (30 Mg ha^{-1}) with sidedressing mineral N (150-200 kg N ha^{-1}). Higher rates of dairy cattle manure or mineral sidedressing N do not produce higher yields, cumulate mineral N in soil increasing the risk of N leaching and reduce N use efficiency. Applying pig slurry, at rates around those legally permitted, to wheat and barley crops at presowing, for a 12-yr period, contributes to increase winter cereal yield and grain protein content. Complementing it with mineral N at sidedressing also increases yield and protein content, but tends to decrease grain density and weight for wheat and barley. Annual applications of dairy cattle manure, for eleven years, increase soil aggregate stability against destabilizing processes from rain or irrigation, both for irrigated and rainfed conditions, improving soil protection against degradation. When pig slurry is applied, it is also observed a trend for aggregate stability increase although not as clear as for dairy cattle manure. Soil content on organic carbon also increases in respect mineral fertilization. This increment is especially important in the light soil organic matter fraction, for both rainfed and irrigated conditions. There is a significative lineal positive relationship between this content and soil aggregates stability. The organic carbon content for the organic matter fraction between 0.05 and 0.2 mm may be a good indicator of soil quality in relation to fertilization management practices. The mentioned manure and slurry applications also increase the abundance of medium-large (>65 µm) pores, producing higher, rain or irrigation, water infiltration and a higher soil permeability. They also increase earthworm abundance, though no relationship has been found between those two parameters.

1.- INTRODUCCIÓ GENERAL

INTRODUCCIÓ

L'agricultura actual ha de produir de manera sostenible i, alhora, contribuir a la solució de problemes ambientals generals, com la mitigació del canvi climàtic. En aquest context, la fertilització orgànica i mineral dels cultius ha de seguir pautes raonades i arribar a nivells més fins d'utilització de nutrients per assolir els objectius múltiples de rendiment i serveis ambientals. Per assolir aquests objectius és necessari tenir informació, entre altres, sobre la resposta dels cultius a les aplicacions de dejeccions ramaderes, que per la seva naturalesa tenen una influència en la disponibilitat de nutrients més enllà del cicle del cultiu en què s'apliquen. Cal conèixer també com aquestes aplicacions influeixen a llarg termini en les característiques del sòl.

Abundància de dejeccions ramaderes i nutrients que aporten als cultius

La Vall de l'Ebre és una zona important en producció ramadera, especialment en porcí. Catalunya i Aragó concentren el 50 % del cens de porcí i el 15 % del cens boví de l'Estat espanyol (MAGRAMA, 2015). Catalunya, en concret, disposa del 27 % del cens de porcí i del 10 % del cens de boví de l'Estat espanyol. L'Estat espanyol, a nivell Europeu, amb el 20 % del cens total de la UE és el segon productor de porcí, només per darrera d'Alemanya (Grup de Gestió Porcina, 2015).

En àrees amb elevada densitat ramadera, les aplicacions de les dejeccions generades tendeixen a ser més abundants, i superiors a les necessitats en nutrients dels cultius. Es provoquen així sortides cap al medi que o bé contribueixen a la contaminació de masses d'aigua o bé a l'enriquiment del sòl en nutrients fins a llindars que no són sostenibles.

Catalunya presenta zones amb una elevada densitat ramadera des de fa anys. Aquest fet ha comportat que, arran de la Directiva nitrats (European Union, 1991) s'hagin designat la major part de zones agrícoles de Catalunya, de secà i de regadiu, com a zones vulnerables a la contaminació per nitrats (Diari Oficial de la Generalitat de Catalunya, 1998, 2004, 2009a i 2015). Actualment, en aquestes zones es limita l'aplicació de dejeccions ramaderes a una dosi anual equivalent a 170 kg N ha^{-1}. També es limita la quantitat de N total que es pot aportar en funció del cultiu i el tipus de maneig que es fa (Diari Oficial de la Generalitat de Catalunya, 2009b).

La producció de dejeccions ramaderes a Catalunya és, doncs, important i, per tant, també ho són les quantitats de nutrients que aquestes contenen i que són susceptibles de ser aplicats als sòls agrícoles. Les dejeccions ramaderes que es generen a Catalunya contenen unes 106.000 tonelades de N (DAAM, 2013), 66.000 en forma de purins, principalment de porcí, i 40.000 en forma de fems, de diversos tipus.

La riquesa en nutrients de les dejeccions ramaderes és molt variable entre diverses espècies i dins d'una mateixa espècie (Pettygrove *et al*., 2009; Yagüe *et al*., 2012; Parera *et al*., 2008 i 2010). Però en la seva composició hi estan presents la major part de macro i micronutrients que les plantes necessiten. Destaca la riquesa en nitrogen, fòsfor i potassi (Teira Esmatges, 2008; Parera *et al*., 2008 i 2010).

Fems i purins presenten característiques diferents que poden influenciar els efectes de les aplicacions d'uns i altres tant sobre els cultius com sobre els sòls (Velthof *et al*., 2000). Ambdós són rics en N, que es troba essencialment en forma amoniacal (al voltant del 75 %) en els purins de porcí (Parera *et al*., 2008; Yagüe *et al*., 2012) i en forma orgànica en els fems. Els continguts en fòsfor i potassi solen ser menors en les dejeccions ramaderes líquides, com els purins, que en les sòlides, els fems. També es diferencien clarament pel contingut en C orgànic (més baix en els purins de porcí que en els fems de boví), la relació C:N (més alta pels fems) i el contingut en matèria seca (més alta pels fems).

Els cultius extensius, receptors de les dejeccions ramaderes

A la zona de Catalunya i Aragó, la producció de cultius extensius, tant de secà com de regadiu, i la producció ramadera són dues activitats econòmiques importants que conviuen territorialment i, sovint també, en les mateixes explotacions agràries.

Els cultius extensius més estesos en aquesta àrea (MAGRAMA, 2014c) són els cereals d'hivern, principalment ordi i blat en secà, que representen un 76 % de la superfície de cultius extensius i un 61 % de la producció. El blat de moro, principalment en les zones de regadiu, representa prop de 120.000 ha, el 10 % de la superfície de cultius extensius, però més d'un 30 % de la producció. Les zones de regadiu suposen més de 600.000 ha en aquesta àrea actualment. En aquest sistema el cultiu de blat de moro és el que té major presència (MARM, 2011).

Les produccions en condicions de regadiu se situen en la part alta del nivell de rendiment. En condicions de secà, la variabilitat en el rendiment és molt elevada i depèn en gran mesura del règim de precipitacions de cada zona.

La major part d'aquesta producció de cultius herbacis s'utilitza en l'alimentació animal (porcí, boví i aviram, principalment).

L'aplicació al sòl de les dejeccions ramaderes produïdes es realitza en les parcel·les gestionades dins la mateixa explotació o en les explotacions properes i aproximadament la meitat de la superfície agrícola rep aportacions de diferents tipus de dejeccions (Sisquella et al., 2004). I així es donen les condicions adequades per una recirculació dels nutrients dins el mateix sistema agrari, sinó dins les mateixes explotacions, si les pràctiques de maneig dels cultius i de la fertilització són les adequades.

Pel que fa als cultius herbacis, els balanços de N i P realitzats a nivell de l'Estat espanyol (MAGRAMA, 2014a i 2014b) constaten que les dejeccions ramaderes representen el 22,5 % del N i el 28,2 % del P que reben els cultius herbacis. Hi ha, però, grans diferències entre zones. A Catalunya el mateix treball mostra que aquests valors són més del doble; el 55,6 % del N i el 61,0 % del P aportat en els cultius herbacis prové de les dejeccions ramaderes aplicades. Aquestes dades estan en línia amb el que succeeix a nivell de la Unió Europea (Eurostat, 2013 i 2014). El balanç total, però, no és neutre. A Catalunya el mateix treball calcula que el balanç de N i P es positiu, més aportacions que extraccions, en 53,9 kg N ha^{-1} any^{-1} i 32,0 kg P ha^{-1} any^{-1}. Per reduir aquests valors és necessari millorar la fertilització dels cultius, especialment les aplicacions de dejeccions ramaderes, que representen més de la meitat de les fonts de N i P en els cultius herbacis.

Els sòls i la seva influència en aspectes ambientals

La pèrdua de carboni orgànic del sòl és un aspecte important (Bot i Benites, 2005; Jones *et al*., 2012) que afecta la sostenibilitat dels sistemes agraris i, especialment, els de l'àrea mediterrània en què els continguts de C orgànic del sòl són baixos o molt baixos (Zdruli *et al*., 2004). La importància rau en la seva influència directa en, entre altres, l'estabilitat estructural del sòl (Tisdall i Oades, 1982) i la protecció d'aquest enfront de processos de degradació (Hallett *et al*., 2012; Porta *et al*., 2003) i en la regulació del canvi climàtic (Batjes, 1996; Lal, 2008).

Les dejeccions ramaderes aplicades al sòl com a fertilitzant poden contribuir al manteniment o augment del contingut en C orgànic (Aoyama *et al*., 1999, Boghal *et al*., 2009; Lugato *et al*., 2014). Es tendeix a associar els ambients mediterranis amb zones de baixa productivitat, però la utilització de sistemes de regadiu i l'adaptació dels cultius i les varietats a les condicions climàtiques locals permeten obtenir produccions elevades en moltes zones. En aquests ambients mediterranis no es disposa d'informació a llarg termini sobre els efectes en rendiment i en la qualitat del sòl de les aportacions de dejeccions ramaderes que permetin establir pautes de maneig de la fertilització orgànica que siguin sostenibles a llarg termini. L'estudi d'aquestes aplicacions en sistemes agrícoles mediterranis és una de les activitats que es proposa desenvolupar a nivell europeu (EIP-AGRI Focus group-5, 2014).

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OBJECTIUS GENERALS

L'objectiu principal d'aquesta tesi doctoral és avaluar l'efecte a llarg termini de les aplicacions de dejeccions ramaderes (fems de boví de llet i purins de porcí d'engreix) en el rendiment i qualitat dels cultius extensius, de regadiu i de secà, i en diferents paràmetres de qualitat del sòl.

Els treballs s'han dut a terme en dos tipus de sistemes agraris diferenciats, en clima mediterrani i sòl calcari, a llarg termini (7-12 anys). Un correspon a un monocultiu de blat de moro en regadiu amb aplicacions de fems de boví de llet abans de la sembra i de fertilitzants nitrogenats minerals en cobertora. L'altre consisteix en una rotació de cereals d'hivern (blat i ordi) en secà amb aplicacions de purins de porcí d'engreix i fems de boví de llet abans de la sembra i fertilitzants minerals en cobertora.

Els objectius específics que s'han plantejat són:

- Avaluar l'efecte a llarg termini de les aplicacions, repetides anualment, de fems de boví de llet i fertilitzant nitrogenat mineral en el rendiment i paràmetres de qualitat del cultiu de blat de moro i la disponibilitat de N pel cultiu.
- Estudiar la incidència a llarg termini de les aplicacions de purins de porc d'engreix abans de la sembra i de N mineral en cobertora, en la producció i qualitat del gra i en l'eficiència en l'ús del nitrogen dels cereals d'hivern en condicions de secà.
- Quantificar els canvis provocats en diferents paràmetres de qualitat del sòl (estabilitat d'agregats, abundància de cucs de terra, fraccions de carboni orgànic i porositat del sòl) per les aplicacions de fems de boví, repetides anualment durant onze anys, en un monocultiu de blat de moro en condicions de regadiu.
- Quantificar els canvis provocats en diferents paràmetres de qualitat del sòl (estabilitat d'agregats, fraccions de carboni orgànic i porositat del sòl) per les aplicacions de fems de boví i purins de porcí, repetides anualment durant més de deu anys, en una rotació de blat i ordi en condicions de secà.

ORGANITZACIÓ DEL DOCUMENT

La presentació dels resultats que es mostren en aquesta tesi s'organitza en set apartats. En primer lloc aquesta introducció general. A continuació, quatre apartats que corresponen cadascun a quatre articles preparats per enviar (capítols segon i tercer) o ja enviats i acceptats (capítols quart i cinquè) a diverses revistes científiques. I, finalment, una discussió general dels resultats obtinguts i un apartat de conclusions del conjunt dels treballs.

En el primer i segon article esmentats s'estudia l'efecte de l'aplicació de diferents tipus de dejeccions ramaderes en la producció de diferents cultius extensius. En el primer es mostren els resultats obtinguts amb l'aplicació combinada de fems de boví i N mineral en cobertora en un cultiu de blat de moro en regadiu en un assaig de set anys de durada. En el segon, les dejeccions que s'estudien són els purins de porcí, en combinació amb aplicacions de N mineral en cobertora, i el seu efecte en una rotació de cereals d'hivern, blat i ordi, en un assaig de dotze anys de durada. En ambdós casos s'han avaluat diferents aspectes de la dinàmica del N en el sistema i l'eficiència en la utilització del N.

En els altres dos articles s'ha estudiat l'efecte que les aplicacions d'aquestes dejeccions han produit en diferents paràmetres de qualitat del sòl en cadascun dels assaigs esmentats després d'onze o dotze anys d'aplicacions anuals de fertilitzants orgànics i minerals.

Finalment, en els apartats de discussió general i de conclusions es sintetitzen els principals resultats obtinguts i les implicacions en les perspectives de recerca i les aplicacions pràctiques d'aquests productes.

2.- DAIRY CATTLE MANURE EFFECTS ON MAIZE PRODUCTION IN IRRIGATED MEDITERRANEAN AREAS

Aquest apartat està basat en l'article:

DAIRY CATTLE MANURE EFFECTS ON MAIZE PRODUCTION IN IRRIGATED MEDITERRANEAN AREAS

Domingo, F., Martínez, E., Rosselló, A., Serra, J., Boixadera, J., Lloveras, J.

Que s'ha preparat per enviar a la revista

European Journal of Agronomy

DAIRY CATTLE MANURE EFFECTS ON MAIZE PRODUCTION IN IRRIGATED MEDITERRANEAN AREAS

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ABSTRACT

The objective of this research, which was conducted over a period of seven years, was to evaluate the effect of continuous applications of dairy cattle manure combined with mineral N on: maize grain yield, grain and plant N content, plant and grain N uptake and soil mineral N, in irrigated sandy soils under Mediterranean conditions.

Two different rates of dairy cattle manure (DCM) application (30 and 60 Mg ha^{-1}) and a control treatment of 0 Mg ha^{-1}of DCM were applied each year, before maize sowing. These DCM rates were combined with four rates of mineral N (0, 100, 200 and 300 kg N ha^{-1}) applied at sidedress.

After three years of continuous applications, it was possible to achieve high grain yields only with manure fertilization, but this was not the case in the first three years. After three years of continuous DCM application, combining 60 Mg DCM ha^{-1} with both 200 kg N ha^{-1} or 300 kg N ha^{-1} at sidedress produced lower grain yields (in most years) than the application of only 60 Mg DCM ha^{-1} without any mineral N sidedress. The results suggest that very high N rates could negatively affect grain yield under our growing conditions.

The highest grain yield (14.3 Mg ha^{-1}, 7-years average) in the trial was obtained with the combination of 30 Mg DCM ha^{-1} and 300 kg N ha^{-1} at sidedress, which resulted in a total N fertilization of 543 kg N ha^{-1} yr^{-1}.

Key words: cattle manure, maize fertilisation, organic fertilisation, soil mineral N

INTRODUCTION

Maize (*Zea mays* L.) and dairy cattle (*Bos Taurus*) production are important economic activities that are often coupled in Northeast Spain. In this area, large amounts of dairy cattle manure (DCM) are produced and are typically recycled as organic fertilizers in neighbouring maize fields (Sisquella *et al*., 2004).

The application of DCM to maize fields has several benefits, including reducing the cost of production, and improving the chemical, physical and biological properties of the soil (Butler and Muir, 2006; Eghball, 2002; Randall *et al*., 2000; Yagüe *et al*., 2016). However, mismanagement of manure (incorrect rates, timing, and method of application) on agricultural land can result in nutrient losses to the environment (nitrate leaching, ammonia volatilization, P runoff, etc.), increased soil salinity or the transfer of pathogens and weeds (Dordas *et al*., 2008).

Groundwater pollution with nitrates is a serious concern in many European regions. To limit the negative impact of livestock production on water quality, the European Union has designated nitrate vulnerable zones where the use of mineral and organic fertilizers is regulated (European Union, 1991). Currently, most of Northeast Spain agricultural land, like several areas of Europe, has been designated a vulnerable zone to nitrate pollution (Diari Oficial de la Generalitat de Catalunya, 2004, 2009 and 2015). In these areas, a maximum of 350 kg N ha^{-1} yr^{-1} can be applied to maize, of which a maximum of 170 kg N ha^{-1} yr^{-1} can derive from organic fertilizers.

In general, the N applied with mineral fertilizer is immediately available for crop production. In contrast, only a fraction of the total N applied with DCM is immediately available for the crop, partly because of the slow-release of organically-bond N over time (Beauchamp, 1983; Jokela, 1992) and partly because of volatilization of ammonia from surface-applied manure. The slow release of the organic N fraction in DCM produces a residual effect that can last several years after application. Some universities of the USA, credit N mineralization of the organic fraction of manure to be 25% in the first year after application, 12% in the second year, and 5% in the third year after application (Ketterings *et al.*, 2003). Consequently, continuous applications of DCM to the same field can increase the cumulative residual effects of DCM.

Therefore, there is increasing interest in understanding the long-term effects of N fertilization of maize with different rates of DCM and mineral N fertilizer on maize yields, soil quality parameters, and nitrate leaching to underground water in Mediterranean conditions (Dordas *et al.*, 2008).

The objective of this study was to evaluate the effect of continuous applications of dairy cattle manure combined with mineral N fertilizer on maize grain yield; plant N content and uptake; and mineral soil N content, in order to maximize grain yields while minimizing the environmental impact, in irrigated sandy soils under Mediterranean conditions.

MATERIALS AND METHODS

Experimental design and maize management

A field experiment was conducted over a 7-year period (2002-2008) at the Mas Badia-IRTA Research Centre at La Tallada de l'Empordà, Spain (42° 03' 2" N; 03° 03' 37" E). The location has a Mediterranean climate with an annual mean temperature of 15.6 ºC (19.5 °C during the maize growing season), and an average annual precipitation of 602 mm (295 mm during the maize growing season) (Figure 2-1). Irrigation is needed to grow maize.

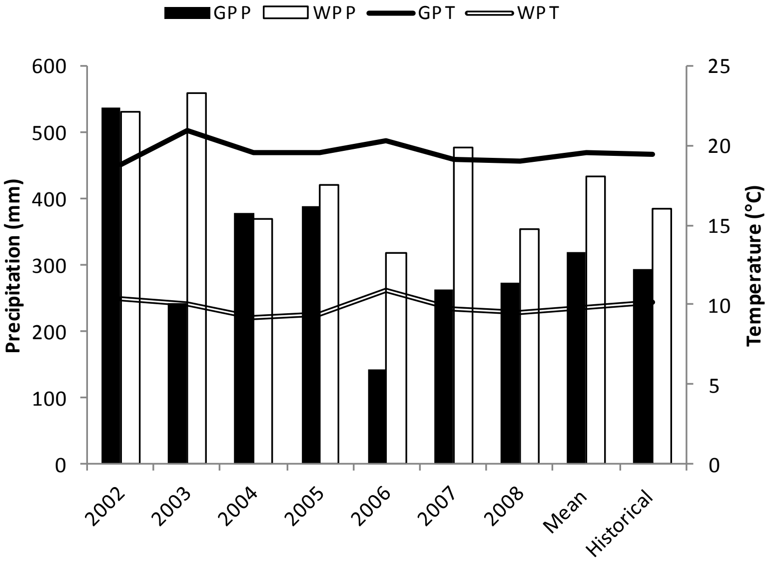

Figure 2-1. Annual precipitation and mean temperature for the experimental period (2002-2008) and for the historical period (1984-2011). Growing Period Precipitation (GP P), Winter Period Precipitation (WP P), Growing Period Mean Temperature (GP T) and Winter Period Mean Temperature (WP T). Growing Period and Winter Period, from April to September and October to March, respectively.

The field site is characterized by a well-drained Xerofluvent Oxyaquic soil (Soil Survey Staff, 1998) with no problems of salinity. The main soil characteristics at the beginning of the experiment are shown in Table 2-1.

The experimental design was a split-plot with four replications. The main plots were three DCM rates (0, 30 and 60 Mg ha^{-1}), referred to as 0DCM, 30DCM, and 60DCM, respectively. The subplots included four mineral N rates (0, 100, 200, and 300 kg N ha^{-1}), referred to as 0N, 100N, 200N, and 300N, respectively. The sub-plot dimensions were 6x10m. The fertilization treatments were randomized in the first year, but thereafter they were applied to the same plots in every year. Dairy cattle manure was applied about three weeks before maize sowing and was incorporated into the soil within a few hours of application. To minimize year-to-year variations in nutrient concentrations (Table 2-2), the manure was always obtained from the same neighbouring dairy farm.

Table 2-1. Soil properties at the beginning of the experiment (2002).

	Depth (cm)		
	0-30	30-60	60-90
Sand (g kg^{-1})	497	425	398
Silt (g kg^{-1})	435	481	486
Clay (g kg^{-1})	68	94	116
pH (1:2.5)	8.4	8.5	8.5
EC (1:5, dS m^{-1}, 25 ºC)	0.19	0.20	0.19
Organic matter (g kg^{-1})	13	10	8
C/N Ratio	9.1	-	-
Total N (mg kg^{-1})	81	-	-
NO_3^--N (mg kg^{-1})	69	22	24
P (Olsen) (mg kg^{-1})	23	-	-
K (NH_4Ac.)(mg kg^{-1})	84	-	-

The same amounts of manure were applied to maize every year, but maintaining specific N doses was difficult due to variations in the composition of the manure. For the 30DCM rate, the total N rate applied to maize ranged from 196 to 279 kg N ha^{-1} yr^{-1} (average=244 kg N ha^{-1} yr^{-1}). For the 60DCM rate, the annual N rates applied ranged from 392 to 558 kg N ha^{-1} yr^{-1} (average = 488 kg N ha^{-1} yr^{-1}) (Table 2-3). Mineral N fertilization was side-dress applied as calcium ammonium nitrate (27 % N) at maize stage V6-V8 and immediately incorporated after application, by furrow construction and ulterior irrigation.

On unfertilized plots (0DCM), 125 kg ha^{-1} of P_2O_5 and 180 kg ha^{-1} of K_2O were applied each year before maize sowing in the form of calcium superphosphate and potassium sulphate. The 30DCM treatment received half of the mineral P and K doses mentioned above to ensure that there was no lack of either of these elements, whereas no mineral P and K fertilizer was applied to plots that received the 60DCM rate.

Table 2-2. Composition of dairy cattle manure for the years of the study (2002 - 2008).

	2002	2003	2004	2005	2006	2007	2008	Mean
Dry matter								
(kg DM Mg^{-1})	301	374	451	328	220	271	316	323
pH	8.7	8.5	8.4	8.7	8.8	8.6	8.6	8.6
Ammonium-N								
(kg N Mg^{-1})	3.3	3.1	1.8	1.9	1.2	1.7	2.0	2.0
Total N (Kg N Mg^{-1})	7.9	9.3	8.7	8.5	6.9	6.5	8.8	8.1
P (kg Mg^{-1})	1.9	2.6	4.0	3.9	4.0	2.5	2.7	3.1
K (kg Mg^{-1})	7.5	8.2	8.3	6.7	4.8	5.3	6.6	6.8

Table 2-3. N inputs (kg N ha^{-1}) from dairy cattle manure fertilisation. Total, inorganic, and organic N applied with dairy cattle manure application rate (DCM) for all the study years. Estimation of the mineralization (decay series) of the organic N fraction applied with DCM during the first 3 years after application.

		N applied with DCM (kg N ha^{-1})			*Estimated mineralization of the organic N applied with DCM (kg N ha^{-1})*			
DCM rate ($Mg\ ha^{-1}$)	**Year**	**Total N**	**NH_4^+-N**	**Organic N**	Year 1 (25%)	Year 2 (12%)	Year 3 (5%)	Total N min (Years 1-3)
30	2002	236	98	138	35	0	0	35
	2003	279	93	186	47	17	0	63
	2004	261	55	206	52	22	7	81
	2005	254	57	197	49	25	9	83
	2006	206	36	170	43	24	10	76
	2007	196	50	146	37	20	10	67
	2008	264	61	203	51	18	9	77
60	2002	472	196	276	69	0	0	69
	2003	558	186	372	93	33	0	126
	2004	522	110	412	103	45	14	161
	2005	508	114	394	99	49	19	167
	2006	412	72	340	85	47	21	153
	2007	392	100	292	73	41	20	134
	2008	528	122	406	102	35	17	154

Maize was planted between March 20th and April 20th (depending on the year), at a rate of about 85,000 plants ha^{-1}. The cultivar “Eleonora” was used in the first three years, “PR32P76” was planted in the fourth and fifth year, and “Helen Bt” was used the last two years of the trial. All the cultivars were FAO cycle 700. Corn stover was always incorporated into the soil after harvest. The crop previously grown in the field was wheat *(Triticum aestivum* L.*)*, with no organic applications or straw incorporation. A pre-emergence herbicide {1L ha^{-1} of Acetochlor [2-cloro-N (etoximetil)-N-(2-etil-6-metilfenil)] 90%} was applied every year to control weeds. At post emergence {1L ha^{-1} of Mesotriona [2-(4-mesil-2-nitrobenzoil) ciclohexano-1, 3-diona] 10%} was also used when needed.

The plots were furrow-irrigated and received 6-7 irrigations per season between June and August, with a water input of approximately 4000-4500 m^3 ha^{-1} of water. The irrigation water applied had no appreciable nitrate content.

Maize was harvested for grain after physiological maturity between September 15th and October 15th, depending on the year.

Measurements

Grain yield was measured by harvesting two complete central rows (1.5 m x 10 m) from each plot. Grain moisture was determined from a 300 g sample taken from each plot (GAC II, Dickey-John, Auburn, IL, USA) and the grain yield was adjusted to 140 g kg^{-1} moisture. The aboveground biomass was obtained at physiological maturity by harvesting plants of two central rows 0.75 m x 4 m at ground level.

The N concentration in the plant and grain at physiological maturity was measured by the Kjeldahl method (AOAC, 1990). Grain and plant N uptake were calculated by multiplying the dry matter yield by the N concentration.

Soil inorganic nitrogen (NO_3^--N and NH_4^+-N) was determined twice during every maize growing cycle: before DCM application and planting **(Nini)** and after harvesting **(Nresidual)**. Soil samples were taken at depths of 0 to 120 cm from four consecutive layers (30 cm each layer). The soil samples were composed of 3 mixed cores per plot. Soil nitrates were extracted using deionized water and measured using test strips with a Nitrachek®

device calibrated according to the standard procedure (Bischoff *et al.*, 1996). About 20 % of the soil samples from each determination were sent to a reference laboratory to double check the results. The soil NH_4^+-N contents were determined by a reference laboratory.

The soil N evolution was calculated for each plot from 2002 to 2008. The N budget (for depths of 0-1.2 m) was also calculated for each plot from 2003 to 2008. Nitrogen mineralization (**N_{min}**) was calculated from the unfertilized plots (0DCM and 0N) by assuming no N-losses with the following equation (Sexton *et al.*, 1996):

$N_{min} = N_{residual} + N_{plant} – N_{ini}$

For the plots receiving manure, **N_{min}** was calculated taking into account the residual effect of the manure (N_{manure}), with the value of the decay series (Table 2-3) (Ketterings *et al.*, 2003).

$N_{min} = N_{residual} + N_{plant} – N_{ini} + N_{manure}$

N_{ini} was the total inorganic (NO_3^--N and NH_4^+-N) initial soil N content and **N_{plant}** was the above-ground N uptake by the aboveground maize biomass at physiological maturity.

The N budget was not considered in 2002 because losses from the control plot were probably not zero (0) due to the high initial soil NO_3^--N content. Nitrogen losses **(N_{lost})** were obtained from the N budget for the fertilized plots (Berenguer *et al.*, 2008):

$N_{lost} = N_{residual} + N_{plant} – N_{ini} – N_{min} – N_{fert}$

N_{fert} was the N applied through mineral or organic fertilization (NH_4^+-N).

N_{lost} was the sum of leached NO_3^--N, N lost due to volatilization and denitrification and N that was unaccounted for. A negative value for **N_{lost}** could be interpreted as a N loss from the soil-plant system, whereas a positive value of **N_{lost}** could be understood in terms of N inputs from the system that had not otherwise been considered.

The results were subjected to analysis of variance using the General Linear Model procedure of the Statistical Analysis System (SAS, 1991).

RESULTS

Weather

During the experimental period, the average temperature during the maize growing period (April to September) was similar to the historical average for the region in almost every year (Figure 2-1). The rainfall during the study period was above the historical mean, although differences occurred from year to year. During the winter season (from October to March) in 2002-03, 2003-04 and 2007-08 (assigned to 2003, 2004 and 2008, respectively, in Figure 2-1), the rainfall was greater than 475 mm, whereas the historical mean was 385 mm. In contrast, 2006 was a dry year, with half of the mean rainfall during the growing period (Figure 2-1).

Grain yield

The average grain yield across treatments varied significantly from year to year (Table 2-4) and ranged from 9.9 Mg ha^{-1} in 2006 to 14.3 Mg ha^{-1} in 2002 (Figure 2-2). No significant interaction was observed between DCM and mineral N on maize yield during the first 3 years of the experiment. During this period, the addition of mineral N fertilizer was required to maximize yields regardless of the DCM rate. The lower DCM rate required the addition of up to 300 kg N ha^{-1} to obtain maximum yields from 2002 to 2004, depending on the year, whereas the higher DCM rate only required the application of 100 kg N ha^{-1} to maximize yields during the first three years. From 2005 to 2008, there was a significant interaction between DCM and mineral N rates on maize yield. During this period, increasing mineral N rates increased maize yields in plots that received 0DCM and 30DCM rates, but not in plots receiving 60DCM rates. In other words, the application of 60 Mg ha^{-1} of DCM was enough to maximize maize yields during the last four years of the study.

Throughout the experiment, the lowest grain productions were obtained with the 0CM-0N, 0CM-100N, and 30CM-0N treatments. It is important to highlight that plots receiving 30 Mg ha^{-1} of DCM always required extra mineral N to maximize yields. Quite similar results were reported by Motavalli *et al*. (1993) and Zebarth *et al*. (1996) in Canada.

Table 2-4. Analysis of variance and average grain yield, grain N content and uptake, plant N content and uptake, soil initial inorganic N, soil residual inorganic N and estimated N losses for all the years studied (2002-2008).

DCM ($Mg\ ha^{-1}$)	**N rate ($kg\ ha^{-1}$)**	**Grain yield ($Mg\ ha^{-1}$)**	**Grain N content (%)**	**Grain N uptake ($kg\ ha^{-1}$)**	**Plant N content (%)**	**Plant N uptake ($kg\ ha^{-1}$)**	**Soil Initial Inorganic N ($kg\ ha^{-1}$)**	**Residual Inorganic N ($kg\ ha^{-1}$)**	**N losses ($kg\ N\ ha^{-1}$)**
0	0	6.3	1.21	78	0.78	142	114	94	0
	100	9.8	1.24	122	0.81	175	110	110	-14
	200	11.2	1.40	158	0.84	210	150	218	-35
	300	12.1	1.52	183	0.95	261	219	256	-86
30	0	10.3	1.34	139	0.82	194	144	123	-246
	100	12.1	1.46	178	0.87	241	173	216	-239
	200	13.8	1.52	209	0.89	279	183	200	-306
	300	14.3	1.56	222	0.96	312	216	268	-347
60	0	12.7	1.46	187	0.86	249	152	148	-474
	100	13.8	1.54	213	0.88	277	197	209	-548
	200	13.1	1.59	207	0.97	289	217	297	-569
	300	13.7	1.62	223	1.01	318	302	429	-584
DCM		**	**	**	**	**	**	**	**
Block		**	**	**	**	**	**	**	*
Error a									
N		**	**	**	**	**	**	**	NS
DCM x N		**	**	**	**	**	*	NS	NS
Error b									
Year (Y)		**	**	**	**	**	**	**	**
DCM x Y		*	**	**	**	**	**	*	**
N x Y		NS	*	*	*	*	**	*	*
DCM x N x Y		*	NS	NS	NS	NS	NS	NS	NS

Dairy cattle manure application rate (DCM), mineral N at sidedress (N). *, ** Significant at the 0.05 and 0.01 levels, respectively. NS - not significant.

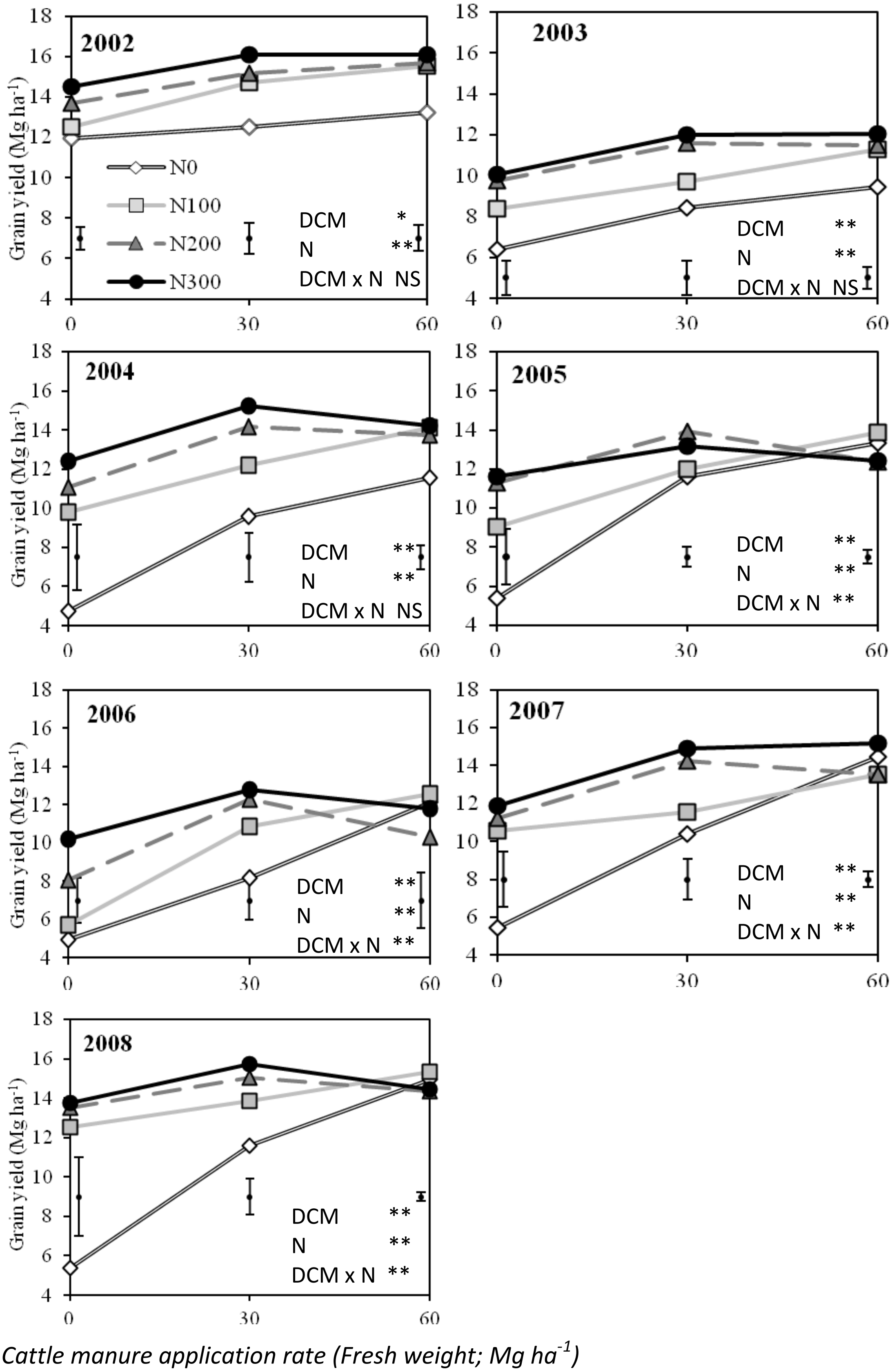

Figure 2-2. Grain yield influenced by dairy cattle manure application rate (DCM) and mineral N at sidedress (N), from 2002 to 2008. *,** Significant at the 0.05 and 0.01 levels, respectively. NS - not significant. The bar indicates the standard deviation.

Common farmer´s practices in Northeast Spain, apply 25-30 Mg ha^{-1} (around 170 kg N ha^{-1}) of organic fertilizer plus 200 to 300 kg ha^{-1} of mineral fertilizer to obtain 13-15 Mg ha^{-1} of maize grain (DAAM, 2006, DAAM, 2013; Sisquella *et al*., 2004).

Plant and grain N content and N uptake

N content and N uptake in maize plants and grains varied from year to year (Figure 2-3). Annual plant N uptake and N content ranged from 84 to 378 kg N ha^{-1} and from 0.68 to 1.07 % of N, respectively (Figure 2-3) and grain N content and N uptake ranged from 1.10 to 1.73 % and from 54 to 269 kg N ha^{-1}, respectively (Figure 2-3). Increasing the mineral N fertilizer rates increased plant and grain N content and N uptake every year. However, these variables increased with increasing DCM rates after the second year of the study (Figure 2-3).

Significant interaction was observed between DCM and mineral N on plant and grain N content and uptake over the study period (Table 2-4). Mainly, due to the interaction between DCM and N in the last four years. In this period, increasing mineral N rates increased plant N uptake at 0DCM and 30DCM plots but not at 60DCM plots. These results are in agreement with the trends previously observed with grain yields.

Inorganic nitrogen in the soil

Soil inorganic N (NO_3^--N + NH_4^+-N) also varied from year to year depending on the amount of manure or mineral N applied at sidedress (Table 2-5), but no interaction was detected between these two N sources. All the fertilized treatments presented high annual initial nitrate nitrogen contents, with levels increasing with higher manure and mineral N application rates.

The initial soil inorganic N was very high in 2002 at the beginning of the study: averaging 198 kg N ha^{-1} (Table 2-5). The annual initial soil inorganic N values were influenced by the residual N content from the previous year and rainfall in the winter period (Table 2-5 and Figure 2-1), with high initial N values when residual N content was high.

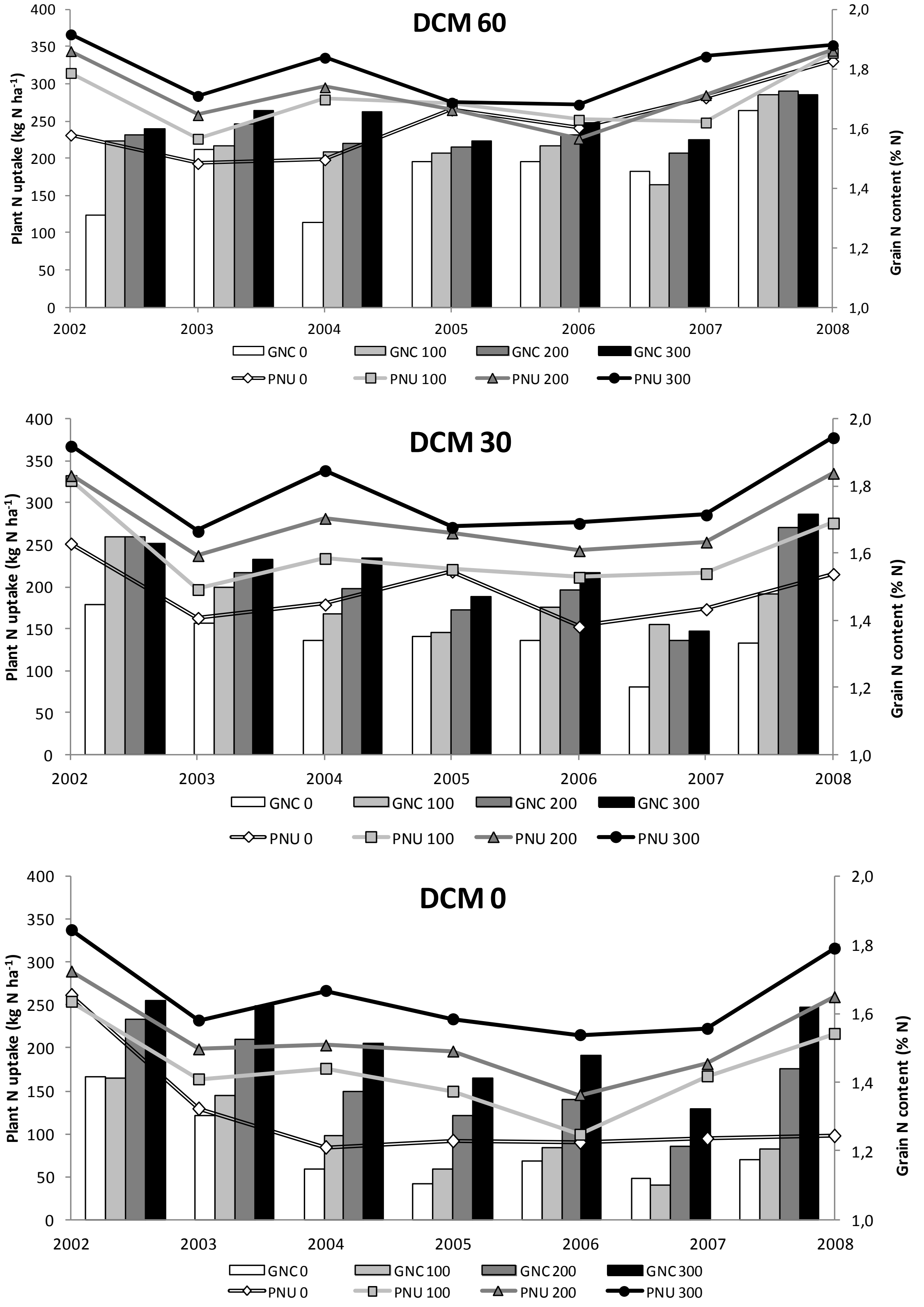

Figure 2-3. Plant N Uptake (kg N ha^{-1}), PNU, and Grain Nitrogen content (%), GNC, for the Dairy Cattle Manure (DCM) rates of 0, 30 and 60 Mg ha^{-1}, combined with the mineral nitrogen rates of 0, 100, 200 and 300 kg N ha^{-1} (N0, N100, N200 and N300, respectively) for all the study years (2002 – 2008).

The residual N values after harvesting were affected by the fertilization rates and crop N uptake (Table 2-5 and Figure 2-3). High inputs of nitrogen in the system resulted in high values of residual N. The 0DCM-300N and 30DCM-300N treatments, showed similar residual values, but lower compared with the 60DCM-300N, which showed the highest residual values of the trial. After three years of manure applications, the rates that optimize grain yields (30DCM-300N and 60DCM-0N) showed much lower values of soil inorganic N values than the 60DCM-300N.

Soil Nitrogen budget

The amount of N mineralized from 2003 to 2008 averaged 75 and 149 kg N ha^{-1} for the 30DCM and 60DCM, respectively (Table 2-3).

On N losses (Table 2-6), it was only in the last year of the trial (2008) that the interaction between DCM and mineral N fertilizer was observed. In 2008, losses were very high and increased with increasing DCM and mineral N application rates (Table 2-6), reaching losses of 926 kg N ha^{-1}. In 2007, there were no statistically significant differences between treatments with respect to N losses (probably due to the great degree of variability), but the plots that received high levels of N fertilization mostly showed the largest N losses (Table 2-6).

Table 2-5. Soil inorganic N content (kg N ha^{-1}) before planting and fertilizing (Ini) and after harvest (Residual) (depth of 0-120cm).

DCM (Mg ha^{-1})	**N rate (kg ha^{-1})**	**2002**		**2003**		**2004**		**2005**		**2006**		**2007**		**2008**	
		Ini	**Residual**	**Ini**	**Residual**	**Ini**	**Residual**	**Ini**	**Residual**	**Ini**	**Residual**	**Ini**	**Residual**	**Ini**	**Residual**
0	0	213	75	98	114	98	104	95	86	62	63	148	88	83	97
	100	140	75	67	206	92	94	109	104	83	56	157	139	123	93
	200	189	345	158	388	136	249	182	213	70	71	184	143	131	122
	300	314	191	186	414	157	132	209	266	67	118	280	432	317	240
30	0	168	97	92	109	159	110	162	118	72	99	194	185	164	145
	100	180	170	100	337	168	144	218	219	109	110	216	382	218	149
	200	236	110	98	146	205	360	193	202	110	116	261	319	177	147
	300	220	177	111	391	248	263	319	276	108	118	258	431	247	217
60	0	161	72	72	195	142	125	155	148	85	102	217	205	231	191
	100	146	121	78	247	196	186	172	215	110	127	311	302	365	263
	200	153	190	130	270	235	373	197	308	125	130	290	470	386	340
	300	257	285	280	309	226	630	344	456	117	242	383	760	505	319
DCM		NS	NS	NS	NS	**	*	*	**	**	**	**	**	**	**
N		NS	NS	*	NS	**	**	**	**	NS	**	*	**	*	**
DCM x N		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Dairy cattle manure application rate (DCM) and mineral N at sidedress (N).

*,** Significant at the 0.05 and 0.01 levels, respectively.

NS - not significant.

Table 2-6. Estimated N Budget.

DCM rate (Mg ha $^{-1}$)	**N rate (kg N ha^{-1})**	**N losses (kg N ha^{-1})**					
		2003	***2004***	***2005***	***2006***	***2007***	***2008***
0	0	0	0	0	0	0	0
	100	57	-43	-39	-48	15	-24
	200	84	-5	-57	-75	-94	-61
	300	15	-179	-93	-126	39	-171
30	0	-307	-331	-256	-194	-132	-256
	100	-153	-352	-308	-262	-16	-345
	200	-402	-225	-356	-324	-186	-345
	300	-240	-408	-502	-388	-139	-403
60	0	-514	-622	-518	-397	-290	-502
	100	-535	-636	-560	-487	-421	-652
	200	-632	-571	-600	-624	-295	-694
	300	-817	-365	-690	-558	-147	-926
DCM		**	**	**	**	NS	**
N		NS	NS	**	**	NS	NS
DCM x N		NS	NS	NS	NS	NS	*

Dairy cattle manure application rate (DCM) and mineral N at sidedress (N).

*,** Significant at the 0.05 and 0.01 levels, respectively. NS - not significant.

DISCUSSION

Grain yield

As several other authors have already reported (Motavalli *et al*., 1993; Zebarth *et al*., 1996; Berenguer *et al*., 2008), there may be no response to mineral N sidedress after the application of high doses of organic N. However, under our conditions, it was not until after three years of continuous manure applications that it was possible to achieve high grain yields when applying only manure fertilization.

The highest grain yields in the trial were obtained with the combination of 30 Mg DCM ha^{-1} and 300 kg ha^{-1} of mineral N at sidedress (Figure 2-2), making a total annual application of 544 kg N ha^{-1}. However, after three years of continuous DCM applications, the combination of 60 Mg ha^{-1} with both 200 kg N ha^{-1} or 300 kg N ha^{-1} at sidedress (in most of the years studied) produced lower grain yields than the application of only 60 Mg DCM ha^{-1} without any sidedress N (Fig. 2-2). These results suggest that very high N application rates can negatively affect grain yield under our growing conditions, even if no lodging was observed. Broadbent and Carlton (1978) in California, also observed yield reductions in fields (averaging 10-11 Mg ha^{-1}) with overfertilised maize, possible due, in their case, to marginal deficiencies of Zn or other micronutrients.

In our study satisfactory grain yields, of about 12 Mg ha^{-1} (Figure 2-2), were achieved with N application rates of around 300 kg N ha^{-1} and with initially moderate soil mineral N content (around 100 kg N ha^{-1}).

Plant and nitrogen uptake

The total average grain N content ranged from 1.21 to 1.62 % (Table 2-4), values that could be considered normal for maize (Watson and Ramstad, 1987). Average plant N contents in our study ranged from 0.78 to 1.01 % (Table 2-4) and were similar to those reported by other authors (Cox and Cherney, 2001).

In our experiment, plant and grain N content and N uptake were highest on the plots that received the greatest applications of fertilizer, but not grain yields (Table 2-4), such as what happened with 60 Mg ha^{-1} of DCM plus 300 kg N ha^{-1} of mineral nitrogen at sidedress. It would suggest some degree of N luxury consumption.

As soil inorganic N depletion occurred throughout the period on low and unfertilized plots, grain and plant N uptake became more responsive to the application of DCM and N fertilizer applied as a sidedress. A similar response was reported by Zebarth *et al*. (1996) in Canada, with yields of 17 Mg ha^{-1} of biomass.

The optimal doses to achieve relatively high N uptakes would be a total amount (organic plus inorganic) of 300-500 kg of N ha^{-1}. Our results suggest that DCM has a similar effect to mineral N fertilization on grain and plant N content.

Soil inorganic nitrogen

At the beginning of the experiment, the soil inorganic N content was high enough to produce good grain yields (averaging 12 Mg ha^{-1}) without any need for N fertilization. Even so, the application of both organic and mineral fertilization increased grain yields.

Due to the N fertilization (whether organic or mineral) and the high soil mineralization, soil inorganic N enrichment occurred at harvest on almost all of the fertilized plots during the experiment (Table 2-5). This soil mineral N enrichment was greater at higher N application rates. This was in line with the findings of Bundy and Malone (1988) and Berenguer *et al*. (2008). Figure 2-4 plots the relative yield of each year for the different DCM rates, depending on the initial N content and the inputs of inorganic N (mineral fertilizer and NH_4^+ from manure) plus the mineralization of organic N. It can be observed that treatments receiving manure needed less amount of initial soil N to achieve high grain yields. This was probably because of the release of the N from manure.

If taking into account that is necessary to have an important amount of initial N content to achieve relatively high grain yields, plots that received manure needed less amount of inorganic initial soil N than plots with applications of mineral N fertiliser (Figure 2-4). Mineralisation and inorganic N from the manure increased N availability for the crop.

Many studies, including those of Zebarth *et al*. (1996) and Nevens and Reheul (2005), have reported that when post-harvest soil nitrate content is high, there is an increased risk of autumn and winter losses associated with rainfall. Although autumn and winter rainfall is normally low in this area, there is still a risk of N losses when sporadic heavy rain events occur, such as those in 2003 and 2007 (Figure 2-1 and Table 2-5).

In 2003, 2004, 2006, and 2008, average soil inorganic N depletion from the residual content from the previous year was observed on all plots. Before planting in 2006, there was 425 mm of rainfall between October-2005 and March-2006 and very low values of N_{ini} N were observed. These results could suggest that a high level of nitrate leaching occurred.

When the initial soil inorganic N content was very high, such as in 2008 (Table 2-5), N losses during the growing period increased significantly (Table 2-6). After the third year of the trial, when mineralization was higher, the amounts of total N found in the soil profile of plots that received only manure fertilization were higher than in the control plots (0DCM-0N).

N budget

Nearly the entire N budget relating to the N applied at sidedress and the DCM treatments produced negative values (Table 2-6). This suggests there were N losses. The majority of these losses could have occurred as nitrate leaching and have been affected by N (organic and/or mineral) fertilization and/or by the initial soil inorganic N content. In 2006 and 2007, the N losses were somewhat lower than in the other years (Table 2-6). These were the driest years of the experiment during the growing season (Figure 2-1). This would seem to corroborate other authors' results, which reported that rainfall has a great influence upon nitrate leaching and therefore on N losses. Berenguer (2008) reported N leaching losses higher than 700 kg N ha^{-1}, in certain years.

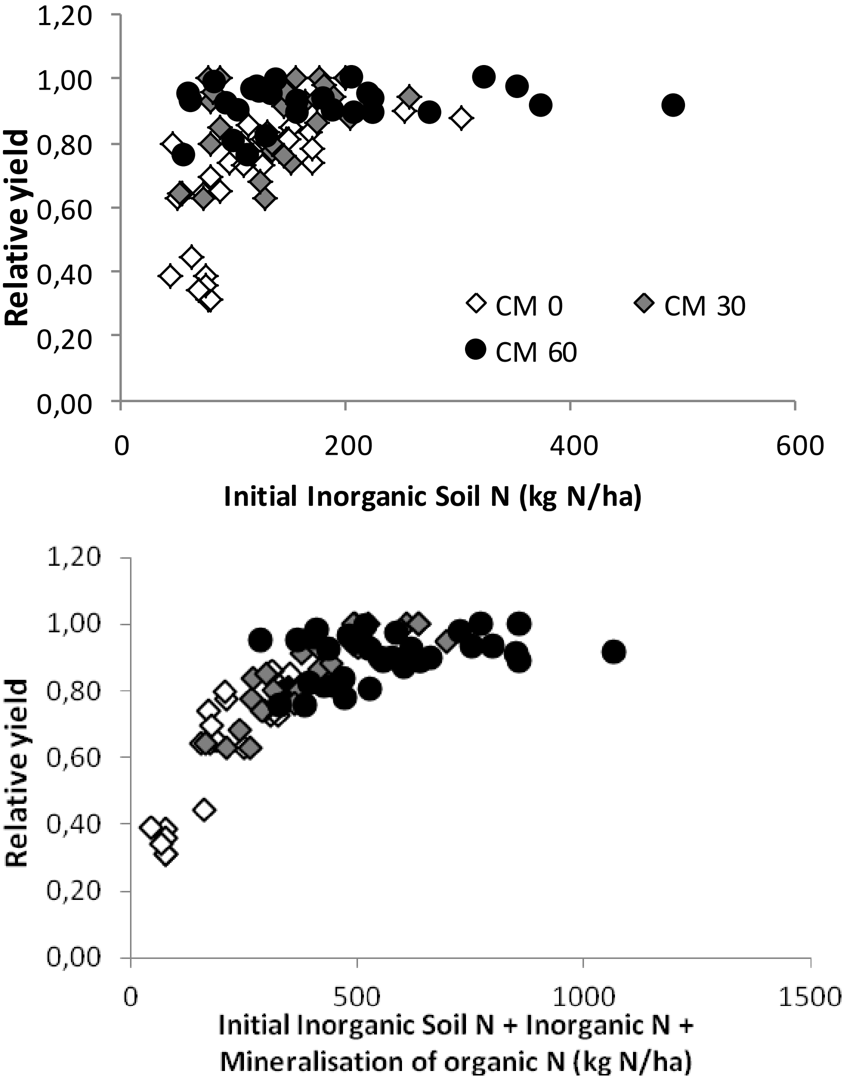

Figure 2-4. Relative yield of each year of the trial, depending on the Initial Soil N (NO_3^- + NH_4^+) and Inorganic N (from mineral fertilizer and cattle manure) and Mineralisation of organic N (decay series of manure).

N losses were smaller on plots fertilized only with mineral N than on those which received DCM treatments (Table 2-6). Working under similar conditions, but with pig slurry, Daudén *et al*. (2004) suggested that N immobilization and/or fixation could have an important influence on the N budget when fertilizing with pig slurry. Therefore some N losses attributed to N leaching can be a transformation of soil mineral N into soil organic N.

During the experiment, the plots fertilised with about 200 kg N ha^{-1} (organic and/or mineral) generally presented the lowest N losses. Similar results have been reported with the application of DCM in North-East Spain in previous studies (Domingo *et al*., 2006).

CONCLUSIONS

Our results suggest that maize (average grain yields of around 15 Mg ha^{-1}) could achieve high yields if fertilising with dairy cattle manure applied at a rate of 60 Mg ha^{-1}. However, this manure rate needed to achieve high yields is above the 170 kg N ha^{-1} of organic material allowed (around 25 Mg ha^{-1} of dairy cattle manure) by the present EU legislation. To comply with it and attain these average maize grain yields, it is necessary to supplement applications of manure at the allowed rates by adding mineral nitrogen at sidedress.

The highest grain yields could be obtained by fertilizing with either a combination of applications (30 Mg ha^{-1} of manure and 200 kg N ha^{-1} at sidedress) or by only fertilizing with DCM (60 Mg ha^{-1}) and then leaving two or three years for N manure mineralization. As the N content of dairy cattle manure can vary from year to year, the N content of the manure should be determined, if possible, before it is applied. A soil nitrate test would also help to achieve the desired soil N level for the crop.

The grain yield was not highest at the high N application rates, although there was a significant increase in grain and whole plant N content. It is therefore not economically feasible, in our conditions, to apply high quantities of N to the soil and this also has the added risk of causing serious levels of pollution.

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3.- EFECTO DE LA APLICACIÓN HABITUAL DE PURINES DE CERDO EN LA PRODUCCIÓN Y CALIDAD DE CEREALES DE INVIERNO

Aquest apartat està basat en l’article:

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F. Domingo-Olivé, E. González-Llinàs, I. Geli-Bosch, A. Rosselló-Martínez, J. Serra-Gironella, J. Boixadera-Llobet

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EFECTO DE LA APLICACIÓN HABITUAL DE PURINES DE CERDO EN LA PRODUCCIÓN Y CALIDAD DE CEREALES DE INVIERNO

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RESUMEN

Se ha llevado a cabo un ensayo de doce años de duración en una rotación de trigo y cebada en secano sub-húmedo con diferentes aportes de purín de porcino en presiembra y de fertilizante nitrogenado mineral en cobertera. La producción de trigo y el contenido en proteína del grano son superiores en los tratamientos en los que se ha aportado purín en presiembra que en los basados en aportes de fertilizante nitrogenado mineral en cobertera. En cebada se observa la misma tendencia pero las diferencias son menos claras. Las aplicaciones de cobertera tienden a producir más grano, pero con menor densidad y peso, y un mayor contenido de proteína en el mismo. En el conjunto de los doce años el rendimiento del cultivo y el contenido en proteína del grano aumentan a medida que las aportaciones anuales de N aumentan. La eficiencia agronómica del N (EAN) y la recuperación aparente del N del grano (RANG) son claramente inferiores cuando se aplican purines en presiembra que cuando los cultivos se fertilizan únicamente con N mineral en cobertera. Este comportamiento se puede justificar a causa de la aplicación de dosis de N no optimizadas en el caso de las aplicaciones de purín, aportándose dosis superiores a las necesarias para las producciones alcanzables en condiciones de secano.

Palabras clave: trigo, cebada, nitrógeno, proteína, suelo calcáreo, clima mediterráneo, fertilización orgánica, sistemas agrícolas mediterráneos

INTRODUCCIÓN

La aplicación de deyecciones ganaderas para la fertilización de cultivos de cereales de invierno es una práctica habitual en las zonas con disponibilidad de estos materiales. Los purines de cerdo, principalmente de granjas de engorde, destacan en este uso entre el conjunto de deyecciones ganaderas por su abundancia y ubicuidad en la mayoría de zonas declaradas vulnerables a la contaminación por nitratos de origen agrario en Catalunya (Diari Oficial de la Generalitat de Catalunya, 1998; Generalitat de Catalunya, 2014) y Aragón. En esta zona se concentra el 50 % de la producción de porcino del Estado Español (Eurostat, 2015) y, por tanto, la utilización de deyecciones ganaderas en la fertilización de los cultivos es generalizada. Los cultivos extensivos son los que reciben la mayor parte de estas deyecciones, especialmente los cultivos de trigo y cebada (4,6 millones de hectáreas en el Estado Español) que se cultivan en secano en más de un 90 % de la superficie.

El efecto de la fertilización con purines de porcino y otras deyecciones ganaderas sobre la producción de los cereales de invierno ha sido estudiado (Bosch *et al*., 2015; Yagüe i Quilez, 2010) en ensayos con aplicaciones consecutivas entre dos y cuatro años. Pero los efectos de la aplicación de estos productos no se limitan al rendimiento de los cultivos sino que puede afectar también a diferentes parámetros de la calidad del grano producido. Además, para una correcta valoración del comportamiento de estos productos como fertilizantes es necesario un enfoque a largo plazo ya que el efecto acumulado de las aplicaciones anuales puede ser importante (Cela *et al*., 2011; Hernández *et al*., 2013).

En este trabajo se ha estudiado el efecto sobre la producción y la calidad del grano (densidad, peso y contenido en proteína) de trigo y de cebada, así como sobre la eficiencia en el uso del N, de las aportaciones anuales de purín de porcino de engorde a lo largo de doce años, con el objetivo de utilizar la información obtenida en mejorar las recomendaciones de uso de estos productos a nivel práctico en las explotaciones agrícolas.

MATERIAL Y MÉTODOS

Se llevó a cabo un ensayo de campo durante un periodo de 12 años (campaña 2001-02 a 2012-13) en la Estació Experimental Agrícola Mas Badia en la Tallada d'Empordà, Catalunya (42° 03' 15" N, 03° 03' 46" E; 17 m snm).

Descripción del suelo y el clima

El ensayo se desarrolló sobre un suelo de textura media, profundo (> 1,2 m), calcáreo, bien drenado, sin elementos gruesos y sin problemas de salinidad. El suelo se clasifica cómo Xerofluvent oxiáquico (DARP, 1995) según las normas de clasificación de USDA (Soil Survey Staff, 1999).

Tabla 3-1. Principales características físico-químicas del suelo al inicio del ensayo (Octubre 2001) para las profundidades de 0-0,30, 0,30-0,60 y 0,60-0,90 m.

	Profundidad		
Parámetro	**0-0,30 m**	**0,30-0,60 m**	**0,30-0,90 m**
Tamaño de distribución de partículas (g kg^{-1})			
Arena (2000 <Ø[‡]< 50 µm)	458	412	538
Limo (50 <Ø< 2 µm)	413	465	351
Arcilla (Ø < 2 µm)	129	123	111
pH (agua; 1:2.5[†])	8.4	8.4	8.2
Conductividad eléctrica (1:5[†]; dS m^{-1}, 25ºC)	0.13	0.18	0.22
Materia orgánica (g kg^{-1})	17	14	7
N Total (g kg^{-1}; Kjeldahl)	0.10	0.08	0.05
Fósforo (mg P kg^{-1}; Olsen)	32	14	7
Potasio (mg K kg^{-1}; Acetato amónico)	306	180	89
Carbonato cálcico equivalente (g kg^{-1})	12.9	12.3	11

[†] Relación suelo: agua destilada.

[‡] Ø: diámetro aparente de las partículas.

Al inicio del ensayo (octubre de 2001) se tomaron tres muestras compuestas del suelo de la parcela a tres profundidades distintas (0-0,30 m, 0,30-0,60 m y 0,60-0,90 m). En cada una se determinaron las principales características de fertilidad de este suelo (Tabla 3-1). El horizonte superficial (0-0,30 m) muestra una textura franca y un contenido en materia orgánica de 17 g kg^{-1}, valor habitual en los suelos de la zona. El suelo es de pH básico y sin problemas de salinidad. Las principales características del suelo al inicio del ensayo se muestran en la Tabla 3-1.

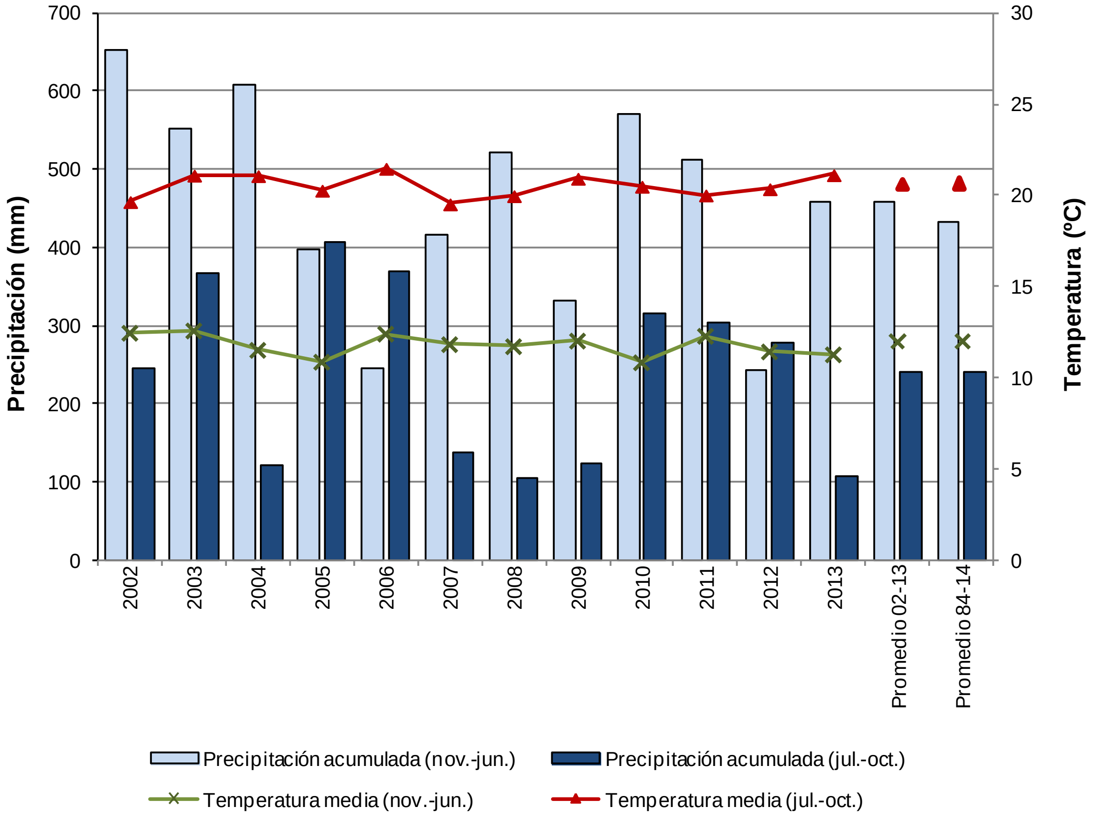

Figura 3-1. Temperatura media (°C) y precipitación (mm) para el período de desarrollo del cultivo (PDC), de Noviembre a Junio, y el período sin cultivo en la parcela (PSC), de Julio a Octubre, para cada año de ensayo, el período total de ensayo y el período histórico (1984-2014). Datos de la Estación Meteorológica de La Tallada d'Empordà (Catalunya).

El clima de la zona es mediterráneo seco según la clasificación de Papadakis (MAPA, 1989). Los datos meteorológicos de la zona (Figura 3-1) se han obtenido de la Estación Meteorológica de la Tallada d'Empordà (Servei Meterorològic de Catalunya, Generalitat de Catalunya), situada a menos de 500 m de la parcela de ensayo. Durante el periodo 1984-2013, la temperatura media anual ha sido de 14,8 °C (12,0 °C durante el periodo de desarrollo del cereal de invierno) y la precipitación media anual ha sido de 672 mm (433 mm durante el periodo de desarrollo del cereal de invierno). La mayor parte de la precipitación se produce en otoño, aunque también pueden producirse lluvias abundantes en primavera. El periodo seco incluye los meses de Junio, Julio y Agosto.

Descripción del ensayo y el manejo de los cultivos

El diseño experimental del ensayo fue en bloques al azar con cuatro tratamientos y cuatro repeticiones. Los tratamientos consistieron en la combinación de diferentes abonados de fondo, dos dosis de purín de cerdo de engorde (0 y 47 m^3 ha^{-1} de media anual), y de cobertera, dos dosis de fertilizante nitrogenado mineral (0 y 50 kg N ha^{-1}): un tratamiento testigo (0PS-0N) sin aplicación de N, uno con aplicación de N solamente en cobertera (0PS-50N), uno con sólo aplicación de purines en fondo (PS-0N) y una combinación de aplicación de purines en fondo con fertilización nitrogenada en cobertera (PS-50N). Las parcelas individuales tenían un tamaño de 30 m^2 (3 m * 10 m). Los tratamientos fueron aleatorizados el primer año del ensayo y se mantuvieron los mismos tratamientos en las mismas parcelas el resto de años.

El purín porcino se aplicó cada año unas dos o tres semanas antes de la siembra del cultivo. De media a lo largo del ensayo se aplicó una dosis de 47 m^3 ha^{-1} en las parcelas correspondientes. La aplicación se realizó de forma manual y se incorporó al suelo en las horas siguientes a la aplicación mediante grada de discos. En cada ocasión se tomó una muestra compuesta del purín aplicado y en ellas se analizó el contenido en nutrientes y otros parámetros relacionados (Tabla 3-2). El purín se obtuvo todos los años de la misma explotación ganadera, cercana a la finca experimental, para minimizar la variación interanual del contenido en nutrientes del purín de porcino aplicado. A pesar de eso, no fue posible mantener la misma dosis de N cada año a causa de las variaciones interanuales en la composición del purín aplicado. Las dosis de nutrientes aplicadas se muestran en las Tablas 3-2 y 3-3. En las parcelas que no recibieron purines (0PS-0N y 0PS-50N), se aplicaron 80 kg ha^{-1} de P_2O_5 y 145 kg ha^{-1} de K_2O cada año antes de la siembra del cereal utilizando superfosfato cálcico (18 % P_2O_5) y sulfato potásico (50 % K_2O). En las que recibieron purines (PS-0N y PS-50N), se aplicaron además 45 kg ha^{-1} de K_2O en forma de sulfato potásico (50 % K_2O).

El fertilizante mineral en cobertera se aplicó en forma de nitrato amónico-cálcico (27 % N). La aplicación se realizó manualmente aproximadamente en el estadio del cultivo de final de ahijado-inicio de encañado (Zadocks 26-30), habitualmente durante la primera quincena de marzo.

Tabla 3-2: Principales características químicas (media ± desviación estándar) del purín de porcino de engorde aplicado en el periodo del ensayo, 2001 a 2013, y cantidad media de nutrientes aplicada anualmente con este producto.

Características	**Purín porcino**	**Nutrientes aplicados anualmente** (media ± desv. estándar) (kg ha^{-1})
Materia seca (%)	6.2 ±2.9	
Materia orgánica (% sms)	59.6 ± 9.4	
N-Kjeldahl (% sms)	2.4 ± 0.3	71 ± 46
N-Amoniacal (% sms)	6.0 ± 6.5	116 ± 76
N-Total (% sms)	8.4 ± 6.7	187 ± 108
Fósforo (P; % sms)	2.8 ± 0.8	100 ± 80 *(228 en P_2O_5)*
Potasio (K, % sms)	4.9 ± 5.5	83 ± 42 *(108 en K_2O)*
Relación C:N	6.1 ± 3.9	

% sms: expresado sobre materia seca

A lo largo de los años de duración del ensayo se cultivó una rotación de cereales de invierno en secano, habitual en muchas zonas de cultivos extensivos: trigo (*Triticum aestivum* L.) los años 2002, 2005, 2008, 2010, 2011 y 2013; y cebada (*Hordeum vulgare* L.) los años 2003, 2004, 2006, 2007, 2009 y 2012.

El manejo general de la parcela se realizó tal y cómo se desarrolla habitualmente en las explotaciones agrícolas de la zona. La siembra se realizó en noviembre o diciembre, usando las variedades y densidades de siembra aconsejadas en la zona, y la cosecha a finales de junio o inicios de julio. La paja del cereal se exportó de la parcela en ocho de los doce años de ensayo. El resto de años la paja del cereal, y el rastrojo en todos los casos, se incorporó al suelo mediante trabajo del mismo con grada de discos y chísel. El suelo se preparó posteriormente, a inicios de otoño, con arado de vertedera (0,25-0,30 m de profundidad). La preparación del lecho de siembra se realizó con rotovator y rulo. El control de adventicias se realizó cada año, en preemergencia y en post emergencia, con herbicidas autorizados de uso habitual en la zona. No se aplicó ningún tratamiento para el control de enfermedades fúngicas.

Tabla 3-3. Descripción de las aplicaciones anuales de purín de porcino, fertilizante nitrogenado mineral y dosis media de nitrógeno total aplicado.

Tratamiento†	**Aplicación anual de purín de porcino antes de la siembra** (m^3 ha^{-1})	**Aplicación de fertilizante nitrogenado mineral en cobertera** (kg N ha^{-1})	**Nitrógeno total aportado anualmente** (kg N ha^{-1})
0PS-0N	0	0	0
0PS-50N	0	50	50
PS-0N	47	0	187
PS-50N	47	50	237

†0PS-0N: Testigo sin aplicación de N;
0PS-50N: Aplicación de fertilizante mineral nitrogenado, 50 kg N ha^{-1}, en cobertera;
PS-0N: Aplicación de purines de cerdo de engorde, 47 m^3 ha^{-1}, antes de la siembra;
PS-50N: Aplicación de purines de cerdo de engorde, 47 m^3 ha^{-1}, antes de la siembra y de fertilizante mineral nitrogenado, 50 kg N ha^{-1}, en cobertera

Medidas realizadas

Cada año, para determinar la producción de grano (kg ha^{-1}) se cosechó una superficie de 15 m^2 en la parte central de cada parcela elemental, con cosechadora de microparcelas. En el momento de la cosecha se tomó una muestra de 1 kg de grano en cada parcela que se utilizó para determinar diferentes parámetros de calidad del grano. La humedad del grano en el momento de cosecha se determinó en una muestra de 300 g (equipo Dickey-John, Auburn, IL, USA; modelo GAC 2100) y la cosecha obtenida en cada parcela se ajustó a una humedad del 13 %. La densidad del grano (kg hl^{-1}), o peso específico, se midió determinando el peso de 0,5 l de grano, por duplicado en cada muestra. El peso de mil granos (g) se determinó manualmente a partir del peso de 50 granos, por triplicado en cada muestra. En los años 2002, 2005, 2008 y 2013 para trigo y 2006, 2007 y 2009 para cebada, una muestra del grano cosechado se envió a un laboratorio externo para determinar el contenido en N del grano (%), utilizando el método Kjeldahl (AOAC, 1990). El contenido en proteína del grano (%) se calculó multiplicando el parámetro anterior por un factor de 5,7 (Teller, 1932).

Se determinó la eficiencia agronómica del N aplicado (EAN) con respecto al grano obtenido en cada tratamiento fertilizado: incremento de la producción de grano respecto al tratamiento testigo en relación a la dosis anual de N aplicada en cada tratamiento (López-Bellido *et al.*, 2006; Fageria y Baligar, 2005). También se calculó la recuperación aparente del N del grano (RANG): incremento del N extraído por el grano respecto al tratamiento testigo en relación a la dosis anual de N aplicada en cada tratamiento (adaptado de López-Bellido *et al.*, 2006).

Para el análisis estadístico de los datos se utilizó el procedimiento GLM ("General Linear Model") del programa estadístico SAS V8 (SAS Institute, 1999-2001). Cuando se observaron diferencias significativas ($p<0,05$) en el análisis de varianza, se realizó una separación de medias con la prueba de rangos múltiples ("Duncan's Multiple Range Test" (DMRT)) a un nivel de probabilidad de 0,05, para los distintos factores (tratamiento y año) y su interacción.

RESULTADOS Y DISCUSIÓN

De los doce años de ensayo, en seis se ha cultivado trigo blando y, en los otros seis, cebada; distribuidos aproximadamente de forma regular a lo largo del periodo de ensayo. El periodo de cultivo es el mismo (Noviembre a Junio) para ambos cultivos.

Condiciones meteorológicas

Las condiciones meteorológicas (Figura 3-1) durante los doce años de ensayo (2002-2013) fueron similares de promedio a la serie histórica (1984-2014). Las temperaturas medias fueron similares a lo largo de estos años, tanto para el periodo de desarrollo del cultivo (PDC), de Noviembre a Junio, como para el periodo sin cultivo (PSC), de Julio a Octubre. La precipitación ocurrida fue muy variable entre años para los dos periodos, PDC y PSC. La precipitación media de los doce años fue de 459 mm para el PDC y de 240 mm para el PSC. En el PDC el año con mayor precipitación fue el año 2002 (651 mm) y el año con precipitación más escasa el 2012 (243 mm).

La precipitación media durante el PDC fue de 519 mm para los años en que se cultivó trigo y de 400 mm, un 23 % inferior, para los años con cultivo de cebada. Para el trigo los años con mayor y menor precipitación durante el PDC fueron el 2002 (651 mm) y el 2005 (398 mm) respectivamente. Para la cebada fueron el 2004 (609 mm) y el 2012 (243 mm).

Producción de grano del cereal de invierno

La producción media alcanzada durante los años de ensayo no difiere entre uno y otro cultivo (4,4 y 4,5 Mg ha^{-1} para el trigo y la cebada respectivamente), a pesar de las diferentes niveles de precipitación en el PDC ocurridos en los años con cultivo de trigo y los años con cultivo de cebada.

Se han observado diferencias estadísticamente significativas entre años (Tabla 3-4) tanto para el cultivo de trigo (α=0,05) cómo para el de cebada (α=0,001). En el caso del trigo la producción media anual varió entre los

3,8 Mg ha^{-1} del año 2010 y los 5,0 Mg ha^{-1} del año 2002, el del inicio del ensayo, con las producciones máximas anuales entre los 4,7 y los 6,3 Mg ha^{-1}, variable cada año (Figura 3-2).

Tabla 3-4. Producción, densidad, peso y contenido en proteína medios del grano de trigo y cebada para los diferentes tratamientos (0PS-0N: Testigo sin aplicación de N; 0PS-50N: Aplicación de fertilizante mineral nitrogenado, 50 kg N ha^{-1}, en cobertera; PS-0N: Aplicación de purines de cerdo de engorde, 47 m^3 ha^{-1}, antes de la siembra; PS-50N: Aplicación de purines de cerdo de engorde, 47 m^3 ha^{-1}, antes de la siembra y de fertilizante mineral nitrogenado, 50 kg N ha^{-1}, en cobertera) y significación estadística de los diferentes factores e interacciones (+ = $p<0,1$; * = $p<0,05$; ** = $p<0,01$; *** = $p<0,001$; NS = no significativo). Para cada parámetro y cultivo, las letras iguales entre tratamientos indican que no se observan diferencias significativas estadísticamente ($\alpha=0,05$) entre ellos.

Tratamiento	**Producción de grano** (Mg ha^{-1})		**Densidad del grano** (kg hl^{-1})		**Peso de mil granos** (g)		**Contenido en proteína** (%)	
Trigo								
0PS-0N	**3,2**	d	**76,4**	ab	**36,6**	a	**10,7**	d
0PS-50N	**4,3**	c	**75,4**	b	**37,0**	a	**11,3**	c
PS-0N	**4,8**	b	**76,7**	a	**37,8**	a	**12,5**	b
PS-50N	**5,4**	a	**75,7**	ab	**35,5**	b	**13,6**	a
Tratamiento	*****		*+*		****		*****	
*Tratamiento * Año*	*****		***		***		***	
Respecto Error Año*Bloque								
Año	***		*****		*****		****	
Bloque	***		*NS*		*NS*		*NS*	
Cebada								
0PS-0N	**3,6**	c	**62,7**	a	**37,8**	a	**7,2**	c
0PS-50N	**4,4**	b	**59,4**	c	**35,0**	bc	**8,3**	b
PS-0N	**4,9**	a	**61,5**	b	**36,4**	ab	**8,4**	b
PS-50N	**4,9**	a	**59,2**	c	**33,8**	c	**9,7**	a
Tratamiento	*****		*****		*****		*****	
*Tratamiento * Año*	*****		*****		***		****	
Respecto Error Año*Bloque								
Año	*****		*****		*****		*NS*	
Bloque	*****		*NS*		*NS*		*NS*	

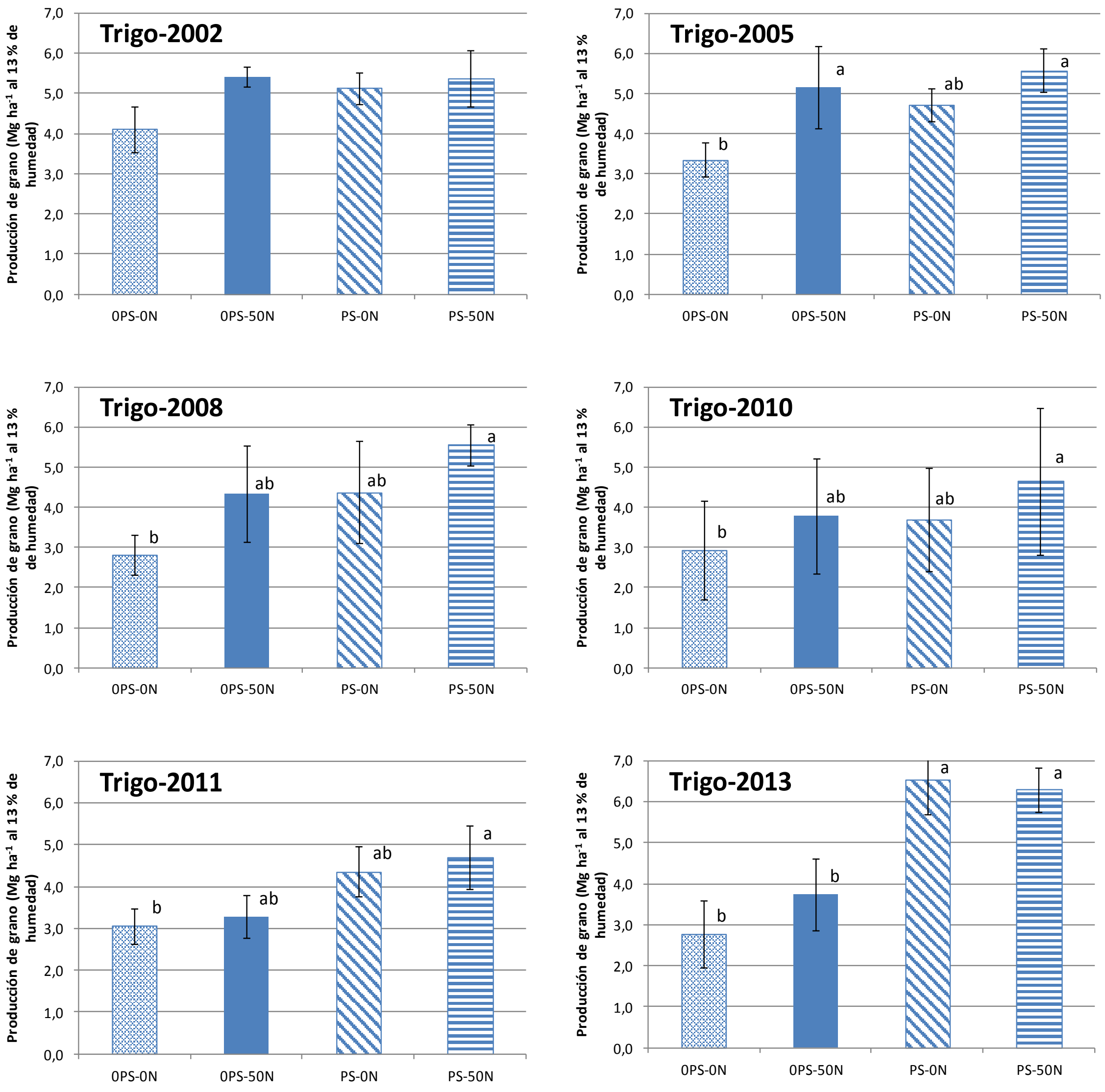

Figura 3-2. Producción de grano de trigo (Mg ha^{-1} al 13 % de humedad) en secano para diferentes años y tratamientos (0PS-0N: Testigo sin aplicación de N; 0PS-50N: Aplicación de fertilizante mineral nitrogenado, 50 kg N ha^{-1}, en cobertera; PS-0N: Aplicación de purines de cerdo de engorde, 47 m^3 ha^{-1}, antes de la siembra; PS-50N: Aplicación de purines de cerdo de engorde, 47 m^3 ha^{-1}, antes de la siembra y de fertilizante mineral nitrogenado, 50 kg N ha^{-1}, en cobertera). Letras iguales sobre las columnas indican que, para ese año, los tratamientos no presentan diferencias significativas estadísticamente (α=0,05) entre ellos.

En el caso de la cebada, la producción media anual fue significativamente diferente el año 2004 (3,7 Mg ha^{-1}) del resto de años en que osciló entre los 4,5 y los 4,7 Mg ha^{-1}. La producción máxima anual del año 2004 fue de 4,3 Mg ha^{-1} y osciló entre 4,9 y 5,8 Mg ha^{-1} para el resto de años (Figura 3-3). Estas producciones, tanto para trigo cómo para cebada, se muestran en línea con las producciones habituales en la zona del ensayo. No se observó ninguna relación entre las producciones medias o máximas anuales y la cuantía de la precipitación ocurrida en el PDC de cada año, para ninguno de los dos cultivos. Probablemente es más importante la distribución de estas precipitaciones en este periodo, o la precipitación en ciertos estadios clave del cultivo, que la cantidad de lluvia total del periodo para explicar la producción media alcanzada.

En conjunto se observan diferencias estadísticamente significativas (α=0,001 para la cebada y α=0,05 para el trigo) entre tratamientos de fertilización (Tabla 3-4), aunque con una significación estadística (α=0,001) de la interacción entre el tratamiento y el año. En el cultivo de trigo la producción fue significativamente diferente entre todos los tratamientos del ensayo, aumentando con el aumento del N aportado (Tabla 3-4). Analizando las producciones anualmente, el tratamiento testigo produce significativamente menos que alguno de los tratamientos fertilizados en todos los años del ensayo en que se cultivó trigo, excepto en el año 2002, al inicio del ensayo (Figura 3-2). No se observan diferencias de producción estadísticamente significativas entre los tratamientos fertilizados excepto en el último año de ensayo (2013) en que los tratamientos que recibieron purín en fondo produjeron más, sin diferencias significativas entre ellos, que los tratamientos sin purín. En el caso de la cebada, la tendencia observada (Figura 3-3) es similar a la descrita para el trigo. De forma conjunta, los tratamientos que recibieron purín como abonado de fondo fueron más productivos, sin diferencias significativas entre ellos, que el tratamiento con aplicación únicamente de fertilizante nitrogenado mineral en cobertera. Y los tres, a su vez, más productivos que el tratamiento testigo (0PS-0N), que se abastece únicamente del nitrógeno mineralizado de la materia orgánica del suelo. El testigo produce menos que alguno de los tratamientos fertilizados en cuatro de los seis años de ensayo con cebada. En los dos últimos años de ensayo con cebada (2009 y 2012), los tratamientos que reciben purín tienden a producir más que el tratamiento con fertilizante mineral.

La producción del tratamiento testigo (0PS-0N), que se alimenta únicamente del nitrógeno mineralizado de la materia orgánica del suelo, se estabiliza a partir del séptimo año de ensayo en unos 2,9 Mg ha^{-1} para el trigo (Figura 3-2) y 3,4 Mg ha^{-1} para la cebada (Figura 3-3).

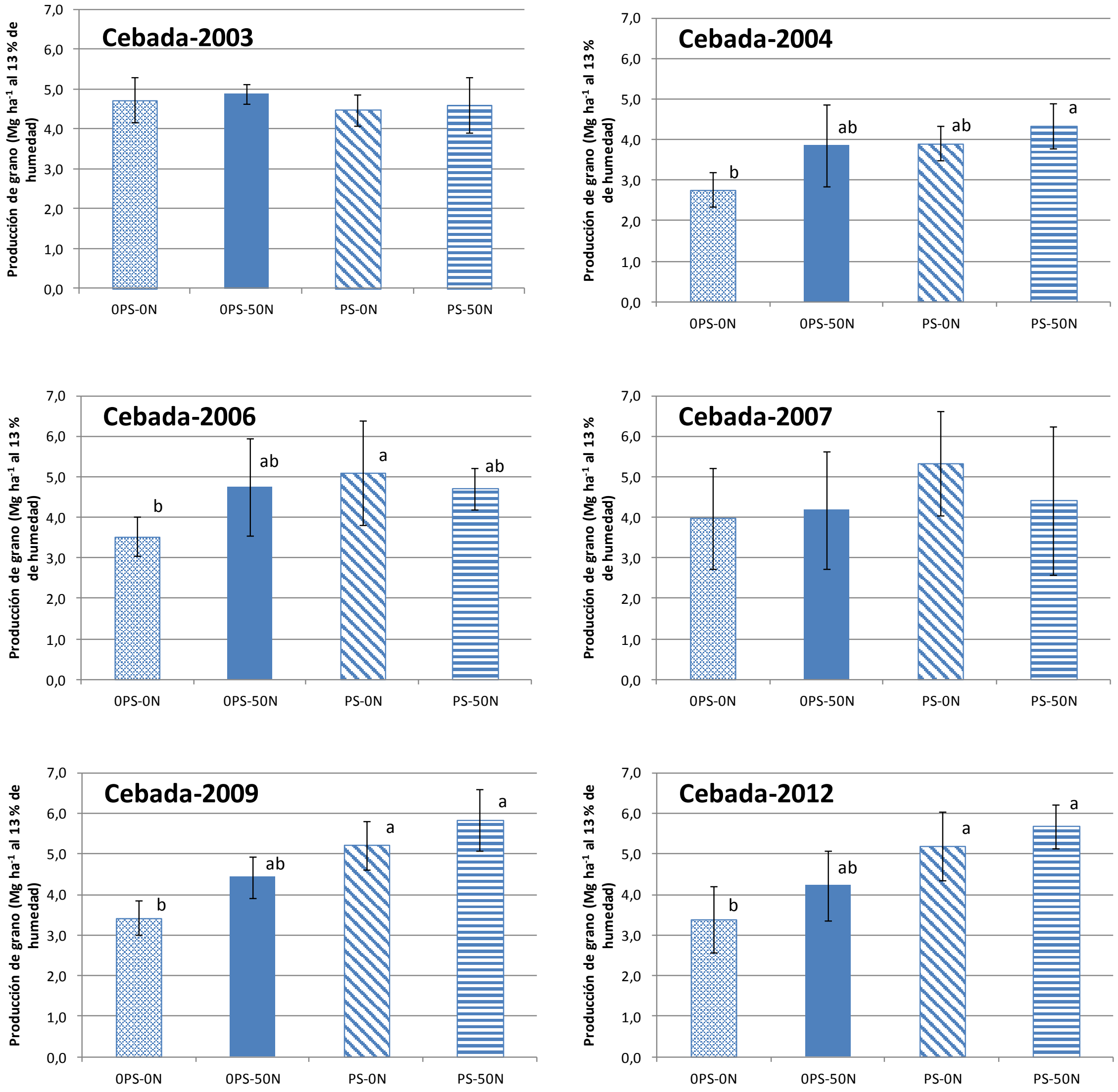

Figura 3-3. Producción de grano de cebada (Mg ha^{-1} al 13 % de humedad) en secano para diferentes años y tratamientos (0PS-0N: Testigo sin aplicación de N; 0PS-50N: Aplicación de fertilizante mineral nitrogenado, 50 kg N ha^{-1}, en cobertera; PS-0N: Aplicación de purines de cerdo de engorde, 47 m^{3} ha^{-1}, antes de la siembra; PS-50N: Aplicación de purines de cerdo de engorde, 47 m^{3} ha^{-1}, antes de la siembra y de fertilizante mineral nitrogenado, 50 kg N ha^{-1}, en cobertera). Letras iguales sobre las columnas indican que, para ese año, los tratamientos no presentan diferencias significativas estadísticamente (α=0,05) entre ellos.

Los tratamientos que habían recibido purines antes de la siembra (PS-0N y PS-50N) no produjeron estadísticamente más que el tratamiento con fertilización nitrogenada mineral (0PS-50N) excepto el último año de ensayo (2013; trigo) en que la producción fue mayor para estos tratamientos. Esta tendencia a una mayor producción de los tratamientos en que se aplica purín, sin diferencias estadísticamente significativas, se observa en los últimos años del ensayo, desde el 2011 (Figuras 3-2 y 3-3).

La aplicación de nitrógeno mineral en cobertera en los tratamientos que habían recibido purines en fondo muestra una tendencia a una mayor producción, sin diferencias estadísticamente significativas, que si sólo se aportan purines en fondo, en la mayor parte de los años en que se cultivó trigo (Figura 3-2). Esta tendencia no se observa en el caso del cultivo de cebada (Figura 3-3).

Mientras que la dosis de fertilizante mineral aplicada está optimizada para la mayor parte de los años, excepto los últimos, de ensayo, las dosis aplicadas con purines son superiores a las necesarias para una producción óptima de cereal. En caso de aplicar dosis menores de N con el purín, el efecto de la aplicación adicional de N mineral en cobertera seria más marcada e importante. En general, aunque con una elevada variabilidad entre años, se obtienen mayores producciones de grano cuando se utilizan purines como fertilizante de fondo, de forma similar a los resultados obtenidos por Hernández *et al*. (2013). Las producciones también son más elevadas si se complementan con fertilización nitrogenada mineral en cobertera (Bosch-Serra, 2010). Estos aspectos son más claros en el caso del cultivo de trigo que en el de cebada. Las producciones acumuladas a lo largo de los años de ensayo son superiores a medida que se aumenta la cantidad de N aplicada, tanto para la cebada cómo para el trigo.

Calidad de grano

Se han observado diferencias estadísticamente significativas entre años (α=0,001) tanto para el cultivo de trigo cómo para el de cebada en la densidad del grano (peso hectolítrico) y el peso de mil granos (Tabla 3-4).

La densidad media del grano de trigo ha sido de 76,1 kg hl^{-1}, valor superior al normalmente requerido comercialmente para este producto (75 kg hl^{-1}). Solamente en el año 2008 (72,6 kg hl^{-1}) no se ha alcanzado este valor. Para el grano de cebada el valor medio de densidad (60,7 kg hl^{-1}) ha sido inferior al normalmente requerido comercialmente (64 kg hl^{-1}), con diferencias interanuales marcadas (entre 54,9 kg hl^{-1} el 2004 y 64,6 kg hl^{-1} el 2006), sólo igual o superior al valor de referencia los años 2006 y 2009 (64,0 kg hl^{-1}). El peso promedio de mil granos ha sido de 40,1 g para el trigo y de 35,7 g para la cebada. Se han observado diferencias estadísticamente significativas entre años para los dos casos. En trigo todos los años son diferentes entre ellos, con valores entre 48,2 g el año 2002 y 34,8 g el año 2011. En cebada también existen diferencias entre años. Los valores oscilan entre los 31,5 g del año 2003 y los 38,6 g del año 2007.

Se han observado diferencias estadísticamente significativas entre tratamientos (Tabla 3-4) tanto en el caso del trigo cómo en el de la cebada, para la densidad del grano y el peso de mil granos. En todos los casos la interacción entre tratamiento y año es significativa. La densidad promedio del grano de cebada es menor cuando se aplica N mineral en cobertera, tanto si se ha aplicado purín en fondo (PS-50N) como si no (0PS-50N). En el caso del trigo se observa una tendencia similar aunque sin diferencias significativas y siempre con valores superiores al de referencia comercial. También se observan diferencias estadísticamente significativas entre la densidad del grano del tratamiento en que se aplican purines en fondo (76,7 kg hl^{-1}) y el tratamiento con aplicación de N mineral en cobertera (75,4 kg hl^{-1}). El peso de mil granos es inferior cuando se aplica purín antes de la siembra y N mineral en cobertera (Tabla 3-4) en el cultivo de trigo. En la cebada se observa una tendencia a un menor peso del grano cuando se aplica fertilizante mineral en cobertera, especialmente si se aplica purín en fondo (Tabla 3-4), aunque las diferencias no son nítidas.

La aplicación de purines en fondo no influye o, en algún caso, aumenta los valores de densidad de grano y peso de mil granos, respecto la aplicación de N mineral solamente en cobertera. Cuando se aplica fertilizante nitrogenado mineral en cobertera, el valor de estos parámetros disminuye respecto las aplicaciones únicamente de fondo o la no aplicación de N.

El contenido promedio en proteína del grano (Tabla 3-4) es mayor en el caso del trigo (11,9 %) que en la cebada (8,3 %). Este contenido aumenta de forma estadísticamente significativa a medida que aumenta el N total aportado, tanto en el cultivo de trigo como en el de cebada. Los valores promedios son superiores en el tratamiento con aplicación de purines y N mineral en cobertera (PS-50N), 13,4 % en trigo y 9,4 % en cebada, que en el que sólo se aplican purines (PS-0N), 12,4 % en trigo y 8,3 % en cebada. En ambos casos se trata de un incremento importante, un punto porcentual en el contenido en proteína del grano. Para el trigo, en dos de los cuatro años en que se ha medido este parámetro, 2005 y 2008, se observan mayores contenidos en proteína, estadísticamente significativos, en el tratamiento con aplicación de purín y N mineral (PS-50N) que en el tratamiento con solamente aplicación de N mineral en cobertera (0PS-50N), con un incremento medio de 3,1 puntos porcentuales. En cebada se observa una tendencia similar, aunque sólo se observan diferencias significativas estadísticamente el año 2006 de los tres con medidas de este parámetro, con incrementos alrededor de 2,5 puntos porcentuales entre estos tratamientos.

El aporte de purín antes de la siembra contribuye a la consecución de un contenido en proteína del grano superior a la aportación de solamente N mineral en cobertera en trigo, pero no en cebada. En conjunto, las aplicaciones de fertilizante nitrogenado mineral en cobertera aumentan de forma marcada el contenido en proteína del grano.

Eficiencias en el uso y recuperación del nitrógeno

Las eficiencias calculadas son mayores en el cultivo de trigo que en el de cebada. La producción de grano (EAN) y la acumulación de N en el grano (RANG) en relación al nitrógeno aportado presentan diferencias estadísticamente significativas entre tratamientos (Tabla 3-5) para el cultivo de trigo, pero no en el caso de la cebada. Los valores obtenidos de EAN son superiores a los obtenidos por Bosch-Serra *et al.* (2015) en un ensayo de cuatro años con aplicación de purines y N mineral en presiembra y cobertera en trigo y cebada de secano, en una zona de menor precipitación. El tratamiento con sólo aporte de N mineral en cobertera (0PS-50N) es el que muestra una mayor eficiencia, tanto en el uso del nitrógeno para incrementar la producción de grano (EAN) cómo en la acumulación de éste N en el grano (RANG), para los dos cultivos.

Tabla 3-5. Eficiencia agronómica del nitrógeno (EAN: kg grano kg N aplicado^{-1}) y Recuperación aparente del N del grano (RANG: kg N en grano kg N aplicado^{-1}) medias del cultivo de trigo y cebada en secano, para los diferentes tratamientos (0PS-0N: Testigo sin aplicación de N; 0PS-50N: Aplicación de fertilizante mineral nitrogenado, 50 kg N ha^{-1}, en cobertera; PS-0N: Aplicación de purines de cerdo de engorde, 47 m^3 ha^{-1}, antes de la siembra; PS-50N: Aplicación de purines de cerdo de engorde, 47 m^3 ha^{-1}, antes de la siembra y de fertilizante mineral nitrogenado, 50 kg N ha^{-1}, en cobertera) y significación estadística de los diferentes factores e interacciones (+ = p<0,1; * = p<0,05; ** = p<0,01; *** = p<0,001; NS = no significativo). Para cada parámetro y cultivo, las letras iguales entre tratamientos indican que no se observan diferencias significativas estadísticamente (α=0,05) entre ellos.

	Eficiencias agronómicas			
Tratamiento	**EAN** (kg grano kg N aplicado^{-1})		**RANG** (kg N en grano kg N aplicado^{-1})	
Trigo				
0PS-0N	**-**		**-**	
0PS-50N	**23,2**	a	**0,54**	a
PS-0N	**12,8**	b	**0,36**	ab
PS-50N	**12,4**	b	**0,34**	b
Tratamiento	*		+	
*Tratamiento * Año*	*NS*		*NS*	
Respecto Error Año*Bloque				
Año	*NS*		*NS*	
Bloque	*NS*		*NS*	
Cebada				
0PS-0N	**-**		**-**	
0PS-50N	**15,0**		**0,32**	
PS-0N	**11,0**		**0,20**	
PS-50N	**7,7**		**0,19**	
Tratamiento	*NS*		+	
*Tratamiento * Año*	+		*NS*	
Respecto Error Año*Bloque				
Año	*		**	
Bloque	*NS*		*NS*	

Este comportamiento se puede justificar a causa de la aplicación de dosis de N no optimizadas en el caso de las aplicaciones de purín, aportándose dosis superiores a las necesarias para las producciones alcanzables en condiciones de secano. Es recomendable adecuar las dosis de purín aplicables a las necesidades reales de los cultivos y no a las condiciones legales permitidas. No se observan diferencias entre las eficiencias obtenidas en los tratamientos en que se aplicó purín, sin (PS-0N) o con (PS-50N) aplicación de N mineral en cobertera, probablemente a causa también de las aportaciones no optimizadas de N.

CONCLUSIONES

Las producciones de trigo y cebada, a lo largo de doce años de cultivo, son superiores a medida que se aumenta la cantidad de N aplicada a estos cultivos. Así mismo, el contenido en proteína del grano también aumenta al incrementar los aportes de N.

Aportar purines antes de la siembra contribuye a aumentar las producciones del cereal de invierno y el contenido en proteína del grano. Complementar estas aportaciones de fondo con fertilizante mineral en cobertera tambien aumenta la producción de grano y el contenido en proteína del mismo. Por contra, la aplicación de N mineral en cobertera tiende a disminuir tanto la densidad como el peso del grano de cereal.

La eficiencia en la utilización del N es marcadamente menor cuando se aplican purines en fondo que en el caso de aportes sólo de N mineral en cobertera. Probablemente por las aportaciones excesivas de N que se realizan al aportar purines en un sistema agrícola de secano, con producciones limitadas. Ajustar las dosis de N aportadas con estos productos puede contribuir a acercar las eficiencias obtenidas a las de los fertilizantes nitrogenados minerales.

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4.- DAIRY CATTLE MANURE EFFECTS ON SOIL QUALITY: POROSITY, EARTHWORMS, AGGREGATES AND SOIL ORGANIC CARBON FRACTIONS

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DAIRY CATTLE MANURE EFFECTS ON SOIL QUALITY: POROSITY, EARTHWORMS, AGGREGATES AND SOIL ORGANIC CARBON FRACTIONS

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ABSTRACT

In the European Union, the maintenance of soil quality is a key point in agricultural policy. The effect of additions of dairy cattle (*Bos taurus*) manure (DCM) during a period of 11 years were evaluated in a soil under irrigated maize (*Zea mays* L.) monoculture. DCM was applied at sowing, at wet-weight rates of 30 or 60 Mg ha^{-1}yr^{-1} (30DCM or 60DCM). These were compared with a mineral-N treatment (300 kg N ha^{-1}, MNF), applied at 6-8 emerged leaves and with a control (no N, no manure). Treatments were distributed in a randomized block design. Factors analysed were stability against wetting stress disaggregation, porosity, soil organic carbon (SOC) fractions and earthworm abundance, studied eight months after the last manure application. The application rate of 30DCM increased aggregate stability and the light SOC fraction, but not the pore volume, nor the earthworm abundance, compared with MNF. The DCM rates did not result in unbalanced agronomic advantages versus MNF, as high yields (15-18 Mg ha^{-1} yr^{-1}) were obtained. In Mediterranean environments, the use of DCM should be encouraged mainly because of its contribution to the light SOC fraction which protects dry macro-aggregates from implosion (slaking) during the wetting process. Thus, in intensive agricultural systems, it protects soil from physical degradation.

KEYWORDS: fertilization, Mediterranean agricultural systems, micromorphology, slaking, soil structure.

INTRODUCTION

The European Union and its Member States are addressing soil quality issues, and setting targets for sustainable land use and soil quality (EU, 2013). Worldwide, vegetation (Cerdà, 1996), revegetation (Yu & Jia, 2014) or revegetation for agricultural uses (Barua & Haque, 2013), specific soil tillage management practices (Nieto *et al*., 2012), the application of different carbonaceous materials (Cely *et al*., 2014; Wick *et al*., 2014) or organic amendments are widely used to improve the physical attributes of degraded agricultural soils (Diacono & Monterruno, 2010; Quilty & Cattle, 2011; Castro *et al*., 2012). The use of manures to maintain or increase soil organic carbon (SOC) is of great interest, as SOC losses are a real threat (Jones *et al*., 2012; Batjes, 2014; Srinivasarao, 2014). In Europe, around 45% of mineral soils have very low or low (0-20g kg^{-1}) SOC content (Rusco *et al*., 2001), but in southern Europe the percentage of topsoil horizons with less than 20 g $kg^{-1}$of SOC can be up to 74% (Zdruli *et al*., 2004). The coarse textured soils are the most affected (Muñoz-*Rojas et al*., 2012) although soil management practices can drive SOC changes (De Moraes Sá *et al*., 2013; Parras-Alcántara and Lozano-García, 2014). Soil organic carbon is an attribute of soil quality because it is one of the principal aggregating agents in soil (Tisdall & Oades, 1982). Furthermore, different authors (Jaiarree *et al*., 2014) pointed out that organic materials should be applied as a priority to soils with low fertility and low SOC in order to enhance soil C sequestration. Also, they favor nutrient recycling in agricultural systems where such residues are produced (i.e. promoting sustainable field management).

Physical fractionation of SOC, using density separation, assumes that biologically significant pools, differing in structure and function, can be obtained. In a long-lasting cultivated soil where stubble is not burned, it separates newly incorporated, partially decomposed debris named the "light fraction" (which includes free and occluded organic C within aggregates) from a more decomposed organic matter (heavy fraction), with a lower C:N ratio, which includes organic matter adsorbed onto mineral surfaces or sequestered within soil aggregates. The light fraction of SOC is a labile source of soil C. It is strongly influenced by factors related to the recent history of organic matter addition (Gosling *et al.*, 2013), meaning that it is sensitive to changes in management practices (Bremer *et al.*, 1994; Gregorich *et al.*, 1997). It is considered to be an early indicator of future (long-term) impacts of management on soil quality (Leifeld & Kögel-Knabner, 2005).

The presence of earthworms is another attribute of soil quality because of their contribution in the conversion of plant residues into soil organic matter. Earthworms help to increase porosity and decrease bulk density, leading to greater soil water infiltration (Lee & Foster, 1991).

Medium and long-term studies on manure fertilization relating to aggregate stability and SOC have been reported (Tripathi *et al.*, 2014). But under Mediterranean climates in particular, there is a gap in knowledge about these potential relationships because management studies have mainly focused on the effects of tillage (Plaza-Bonilla *et al.*, 2013) where “no tillage” or “minimum tillage” increased the proportion of macroaggregates together with gains in SOC content, or on the effect of slurries (Yagüe *et al.*, 2012) which have a positive impact on aggregate stability and soil microbial biomass. The gap is relevant, because highly productive Mediterranean climates exist on several continents (Bosch-Serra, 2010). Climatic conditions can also induce different responses (Whitbread, 2003) although aridity, which leads to soil structure degradation processes becoming more active (Cerdà, 2000), is one of the most relevant.

The experimental area is representative of northeastern Spain where soils are characterised by low SOC content and climate by erratic rainfall (Beguería *et al.*, 2011). Manures are readily available because dairy cattle are raised locally (Idescat, 2009). Recently, as the area has been classified as a nitrate vulnerable area (Generalitat de Catalunya, 2014), management policies focus on water quality preservation. However, soil disaggregation exists and crust formation in the fields is evidence of soil quality problems, which lead to difficulties in crop emergence and poor water infiltration, and enhance laminar flux, which can transport disaggregated materials.

The breakdown of soil aggregates by implosion (slaking), caused by the penetration of water into soil dry aggregates, is increased when the soil surface dries between rain or irrigation events. Slaking is the main destabilizing mechanism for aggregate disintegration in the Ebro basin (Amézqueta *et al.*, 2003). At field level, disaggregation by wetting stress increases the risk of soil erosion (Mataix-Solera *et al.*, 2011).

Macropores and mesopores (100-1000 µm) increase as manure rates increase (Miller *et al.*, 2002) but microporosity also depends upon the organic material applied (Pagliai & Antisari, 1993). Pore size distribution and total porosity affects and is affected by almost everything that occurs in soil: movement of water and air, the transport and reaction of chemicals, and the presence of roots and other biota (Nimmo, 2004). Our hypothesis is that the regular use of manures in a Mediterranean agricultural system with low SOM content, helps in avoiding slaking. Furthermore, it could affect other physical (i.e. porosity and pore size and shape) and biological (i.e. presence of earthworms) properties related to aggregation.

The aim of this study was to assess the effect of fertilization management (mineral or dairy cattle manure) on soil quality parameters under a maize (*Zea mays* L.) crop that was maintained as a monoculture during 11 growing seasons, under irrigation. Soil quality studies focused on SOC fractions and the stability of aggregates to wetting stress (slaking), soil porosity and earthworm abundance. The defined objectives were: (i) to assess changes in soil organic carbon physical fractions; (ii) to evaluate soil macroaggregate stability under a slaking breakdown mechanism; (iii) to study potential relationships between macroaggregate stability to wetting stress and the different soil organic carbon fractions; (iv) to evaluate other related impacts of SOC such as porosity distribution and pore size and shape; (v) to quantify changes in earthworm abundance and their potential relationship with macroaggregate stability or porosity.

MATERIALS AND METHODS

Soil and climate description

The experiment was established in 2002 in Tallada d'Empordà, Girona, NE Spain (altitude 18 m a.s.l., lat. 42° 3' 2" N, long. 3° 3' 37" E.) The soil studied has a loam texture in the upper layer (0-0.30 m) and a soil organic carbon content of 7.6 g SOC kg^{-1}. It is well drained and no salinity is present (Table 4-I). The soil is classified as Oxiaquic Xerofluvent (Soil Survey Staff, 2014).

Table 4-I. Selected soil physical and chemical characteristics of the experimental site. Samples (0-0.30 m) were obtained at the start of the fertilization experiment (October 2002).

Parameter	Value
Particle size distribution (g kg^{-1})	
Sand (2000 <Ø[‡]< 50 µm)	497
Silt (50 <Ø< 2 µm)	435
Clay (Ø < 2 µm)	68
pH (water; 1:2.5[†])	8.4
Electrical conductivity (1:5[†]; dS m^{-1}, 25ºC)	0.19
Organic matter (g kg^{-1})	13.0
Total N (g kg^{-1})	0.8
Phosphorus (mg P kg^{-1}; Olsen)	23
Potassium (mg K kg^{-1}; Ammonium acetate)	84

[†] Relation; soil: distilled water.

[‡] Ø: particle apparent diameter.

The area has a dry Mediterranean climate according to Papadakis classification (MAPA, 1989). The annual average temperature is 15.6 ºC and summer temperatures are high (on average 23 ºC). Average annual precipitation is 602 mm. Potential evapotranspiration is also high based on Thornthwaite's equation (~827 mm yr^{-1}). Most rain falls in autumn with storm events in September-October-November which can enhance runoff processes if the soil is bare. But these events may also occur in springtime, during the maize sowing period, when crust formation can strongly affect crop emergence and establishment. The dry period includes July and August.

Description of the experiment

The experimental field was cropped with maize (*Zea mays* L.) as an irrigated monoculture, until November 2012. Every year seeding was done in March-April and harvest in September. During each cropping season of the experimental period (2002-2012), tillage and fertilization management were maintained just the same. The stubble was left in the field and was incorporated in the soil, after each annual harvest, by disc-harrowing tillage. At the end of autumn or in early winter, tillage was done by a mouldboard plough (~ 25-30 cm depth).

Fertilization with dairy cattle manure and mineral fertilizer treatments were included in a broad experiment aimed at obtaining fertilizer assessments in terms of yield. The treatments were in a randomised complete block design with three replicates (blocks). From them, one inorganic fertilizer treatment and two organic amendment treatments were selected (Table 4-II), plus a control (no N, no manure applied). Treatments were chosen according to historical maximum grain yields which were between 15 and 18 Mg ha^{-1} at 14% moisture content (Fig. 4-1), without significant differences between chosen treatments of dairy cattle manure (DCM) and mineral nitrogen fertilizer (MNF). Manure treatments were: DCM, applied only at sowing, at wet-weight rates of 30 and 60 Mg ha^{-1} yr^{-1} (named 30DCM-0 and 60DCM-0, respectively; Table 4-II). The lowest DCM rate took into account the legislation in force at the start of the experiment, which established a maximum amount of 210 kg N ha^{-1} to be applied annually from organic sources. At this rate, the annual average amount of organic carbon applied in the period 2002-11 was 2.4 Mg ha^{-1} and 3.3 Mg ha^{-1} in the 2012 cropping season (Table 4-II). It can also be expressed as an average manure equivalent nutrient amount for the period 2002-2012 of 230±60 kg N ha^{-1} yr^{-1}, 76±33 kg P ha^{-1} yr^{-1} and 210±94 kg K ha^{-1} yr^{-1}. It was complemented with 27 kg P ha^{-1} yr^{-1} as calcium superphosphate and 75 kg K ha^{-1} yr^{-1} as potassium sulphate. When the manure rate was doubled (60DCM-0), no PK mineral fertilizer was added. Manures were incorporated by disc-harrowing just before sowing.

Table 4-II. Description of annual fertilization treatments with averages of the organic carbon (C) applied. Fertilizers (mineral or from different dairy cattle manure rates) were annually applied at sowing or when the crop had six-eight visible leaves (V6-V8).

	Annual fertilizer treatment		**2002 to 2011 (10 yr)**	**Fertilization at sowing in 2012**
Treatment†	**Sowing**	**V6-V8**	---------- Mg C ha^{-1} yr^{-1}	-----
0-0	0	0	0	0
0-300MNF	0	300	0	0
30DCM-0	30	0	2.4 (±0.6)	3.3
60DCM-0	60	0	4.8 (±1.2)	6.6

Numbers in brackets are the standard deviation.

†MNF: mineral nitrogen fertilizer (calcium ammonium nitrate, 27 % N), applied when the crop has six-eight leaves. Number behind indicates the applied rate of 300 kg N ha^{-1} yr^{-1}.

DCM: dairy cattle manure. Numbers indicate the average theoretical applied wet-weight rate: 30 Mg ha^{-1} yr^{-1}, or 60 Mg ha^{-1} yr^{-1} at sowing.

The MNF treatment consisted of 300 kg N ha^{-1} (named 0-300MNF) applied as calcium ammonium nitrate (27 % N) at the V6-V8 Zadocks' development stage (late May). Mineral fertilizer and control (0-0) treatments received, at sowing time, 55 kg P ha^{-1} yr^{-1} as calcium superphosphate and 150 kg K ha^{-1} yr^{-1} as potassium sulphate. The control was maintained throughout all growing seasons.

Sampling and analysis of manures and soil properties

In every cropping season, at manure application time, a composite sample of manure applied was analysed (Table 4-II). Organic matter was analysed according to the total volatile solids methodology which in our case includes ashing at 550ºC for 6 h in a muffle furnace. The loss of weight equals the total volatile solids (Chatterjee *et al.*, 2009). The carbon content was obtained by dividing by a coefficient of 1.82 according to the molecule that is considered to be representative of the organic matter present in manures.

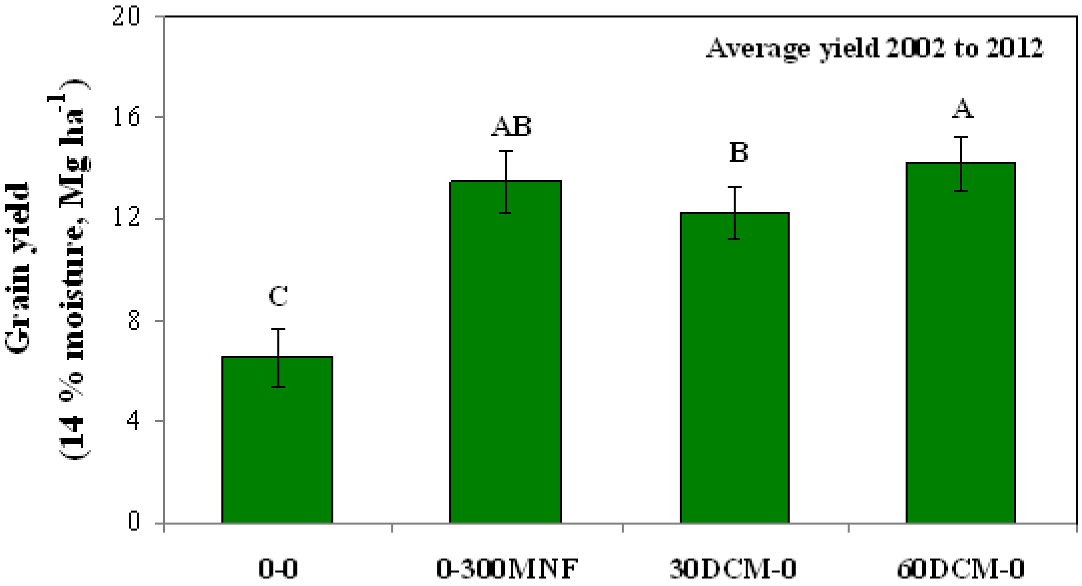

Figure 4-1. Average grain yield (14 % moisture content) of the period from 2001 to 2012 for each fertilization treatment: 0-0 or the control (no N, no manure applied); 0-300MNF: mineral N fertilizer (calcium ammonium nitrate, 27 % N) applied at rate of 300 kg N ha^{-1} yr^{-1} when six-eight leaves were visible; 30DCM-0 and 60DCM-0: dairy cattle manure applied at wet-weight rate of 30 Mg ha^{-1} yr^{-1}, or 60 Mg ha^{-1} yr^{-1} at sowing. Mean values of abundance followed by a different letter are significantly different at the 0.05 probability level based on the Duncan Multiple Range Test. Bars represent the standard error of three replicates.

Soil samplings were run for each fertilization treatment in each block after the last harvest, which means eight-nine months after the last manure application (28th March 2012) and incorporation (2nd April 2012). To assess aggregate stability and organic carbon fractions, samples were taken on 12th November 2012. In each plot, four individual points were sampled (0-0.10 m depth) and a composite soil sample was obtained. The three composite samples for each treatment (from the three blocks of the experiment) were air-dried, stored and sieved (2 mm) just before the different analytical procedures were carried out. Two days later (14th November) sampling was done (0-0.20 m depth) in the same plots to evaluate earthworm abundance. Finally, in December 12th, undisturbed soil samples (0-0.05 m depth) were taken in order to study porosity through image analyses of soil thin sections.

Water-stable aggregates (WSA_{MOD}) without sample pre-wetting and mean weight diameter of aggregates (MWD_{FW})

Aggregate stability was evaluated according two methods: the standard single-sieve technique in distilled water and the multiple-sieve technique in ethanol.

Each composite sample (one per plot) was divided into four subsamples and all of them were evaluated for aggregate stability, which means 12 analyses for each treatment as treatments were replicated in three blocks. The standard stability test for water-stable aggregates (WSA) was modified; in that sample pre-wetting (WSA_{MOD}) was avoided, because slaking decreases as the initial water content increases (Truman *et al.*, 1990). In the WSA_{MOD} test, four grams of 1-2 mm air-dried sample were directly placed on a 0.25 mm opening sieve and transferred to a Yoder apparatus for disaggregation following the procedure of Kemper & Rosenau (1986). Soil remaining on the sieve was oven-dried (105 ºC, 24h) and weighed to give the “aggregate stable-mass” which was expressed as a percentage of total mass. The mass of sand in both parameters was previously discounted.

The resistance to slaking was also quantified as the mean weight diameter of aggregates remaining after fast wetting (MWD_{FW}). The methodology followed Le Bissonnais (1990) as modified by Amézqueta *et al.* (1996). The disrupting mechanism was applied to 4 g of air-dry, 1-2 mm diameter aggregates. Aggregates were placed in 0.25 mm opening sieves and gently immersed for 10 minutes in 100 mL of deionized water. The sieves were transferred to the modified Yoder apparatus and disaggregation consisted of mechanically moving the sieves immersed in ethanol (95 %) up and down, 10 times over a distance of 1.3 cm. The fraction >0.25 mm was oven dried (105 ºC, 24h) and dry sieved for 1 minute on a column of four 6.5 diameter sieves with hole openings of 2.0, 1.0, 0.5, and 0.25 mm using a standard mechanical sieve shaker.

The aggregate stability for each treatment was expressed as MWD (µm). It was calculated as Eq. [4-1]:

$$\mathrm{MWD_{FW}} = \sum_{i=1}^{n} Wi \times Di \times 10^3 \qquad \text{Eq. [4-1]}$$

Where *n* corresponds to the number of aggregate size fractions considered in the analysis (in this case four size class: <0.25 mm; ≥0.25 mm to 0.5 mm; ≥0.5 mm to 1mm; ≥1mm to 2mm), Di is the mean diameter of aggregates that potentially can stay in the *i*th and *i*+1 th sieves which were: D_1=0.125 mm; D_2=0.375 mm; D_3=0.75 mm; D_4=1.5 mm; and Wi is the mass percentage of each fraction (dry weight of aggregates in the *i*th size fraction (g) divided by the sum of total sieved soil dry weight fractions (g)).

Soil organic carbon fractions

For each sample, five soil density and particle size fractions were obtained according to the procedure NF X 31-516 established by AFNOR (2007). According to it, the soil particle fraction sizes obtained were: <0.05 mm, ≥0.05-0.2 mm and ≥0.2-2 mm. The two upper size fractions were divided by flotation into two density fractions each: light (the fraction that floats in water) and heavy (the rest). The light fraction was analysed following the total volatile solids method. In the heavy fractions and in the smallest size one (<0.05 mm), as they are linked to the soil mineral components, the oxidizable SOC was determined by dichromate oxidation and subsequent titration with ferrous ammonium sulphate following the Walkley-Black method (MAPA, 1994).The same method was used for all initial soil composite samples as it is the routine method used in agronomic soil laboratories.

Earthworm abundance

Earthworms were sampled from an excavated hole in field conditions. A template was used to define a 0.25 m x 0.25 m area in two randomly chosen locations in each plot, and samples were obtained from the defined area in a 0-0.20 m depth (Baker & Lee, 1993; Smith *et al*., 2008). No chemical expellant was used. Earthworms in each sample were removed by hand-sorting. Abundance was measured for intact and fragment earthworms.

Soil porosity

The undisturbed samples were dried at room temperature and impregnated with polyester resin with a fluorescent dye (Uvitex©). One vertical thin section (5 cm wide, 13 cm long) was made from each block, according to the procedures of Stoops (2003).

From each thin section two images (42 x 31.5 mm each) were obtained under two light conditions: parallel polarisers and crossed polarisers plus a third image under an ultraviolet incident light. They were processed with ImageJ (Rasband, 2008) to obtain digital binary images from which the porosity, associated with pores with an apparent diameter (AD) >25µm (the minimum threshold allowed by the established procedure) was analysed. Pore-size distribution analysis of each image was based on an open mathematic algorithm: the Quantim4 library (Vogel, 2008). The area occupied by pores was divided in four intervals according to the pores' apparent diameter: 25-65 µm; 65-100 µm, 100-200 µm, 200-400 µm and >400 µm. Shape descriptors used followed Ferreira & Rasband (2012): Circularity, with a maximum value of 1 indicating a perfect circle (4π pore area / pore perimeter^2); Aspect ratio, or the ratio of the particle's fitted ellipse (major axis / minor axis); and Solidity (area of the pore / convex area of the pore).

Data analysis

All statistical analyses were performed using the SAS V8 (SAS Institute, 1999-2001) statistical software. When differences, according to the analyses of variance (ANOVA) were considered significant ($p<0.05$), Duncan’s Multiple Range Test (DMRT) was computed for comparing all possible pairs of means at the 0.05 probability level, with the exception of the earthworm abundance where the DMRT was done at the 0.10 probability level.

RESULTS

In all treatments, the WSA_{MOD} and MWD_{FW} values were in the interval between 25.3 to 35.0 % and 244 to 325 µm respectively (Table 4-III). No significant differences were found between the MNF treatment and the control (Table 4-III). However, resistance to slaking, evaluated as WSA_{MOD} and MWD_{FW}, was significantly improved by long-term manure addition, with no differences between the two manure rates (Table 4-III).

Table 4-III. Average values (n=12) of the mass percentage of water-stable aggregates (WSA_{MOD})[‡] and of the mean weight diameter after a fast wetting (MWD_{FW})[§], associated with different fertilization practices maintained during a period of 11 years in a maize crop.

Treatment[†]	**WSA_{MOD} (%)**[‡]	**MWD_{FW} (µm)**[§]
0-0	25.31 (4.76) B	244.03 (8.70) B
0-300MNF	25.26 (6.08) B	247.28 (4.46) B
30DCM-0	34.25 (14.12) A	324.95 (16.16) A
60DCM-0	35.03 (1.24) A	309.65 (13.21) A
Significance[¶]	*	**

Numbers in brackets are coefficients of variation (%).

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

[†] MNF: mineral nitrogen fertilizer applied as calcium ammonium nitrate (27 %, N); the number behind indicates the applied rate of 300 kg N ha^{-1} yr^{-1} at six-eight visible leaves. DCM: dairy cattle manure; numbers indicate the average theoretical applied rate of 30 Mg ha^{-1} yr^{-1} or 60 Mg ha^{-1} yr^{-1} at sowing.

[‡] WSA_{MOD}: Water aggregate stability from Kemper and Rosenau (1986) method and its modification without pre-wetting.

[§] MWD_{FW}: mean weight diameter after fast-wetting, according to Le Bissonnais (1990) and modified by Amézqueta *et al*. (1996).

[¶] Mean values in a column followed by different letter are significantly different at the 0.05 probability level based on the Duncan Multiple Range Test.

The SOC content obtained by dichromate oxidation in the bulk soil ranged from 7.3 to 14.6 g C kg soil^{-1} (Table 4-IV). Although dichromate oxidation does not recover all the organic carbon (Skjemstad & Taylor, 1999), in both manure treatments it was significantly higher than those from the MNF treatment or the control. The more stable carbon (size<0.05 mm) was also significantly improved with the manure addition at the highest rate (Table 4-III).

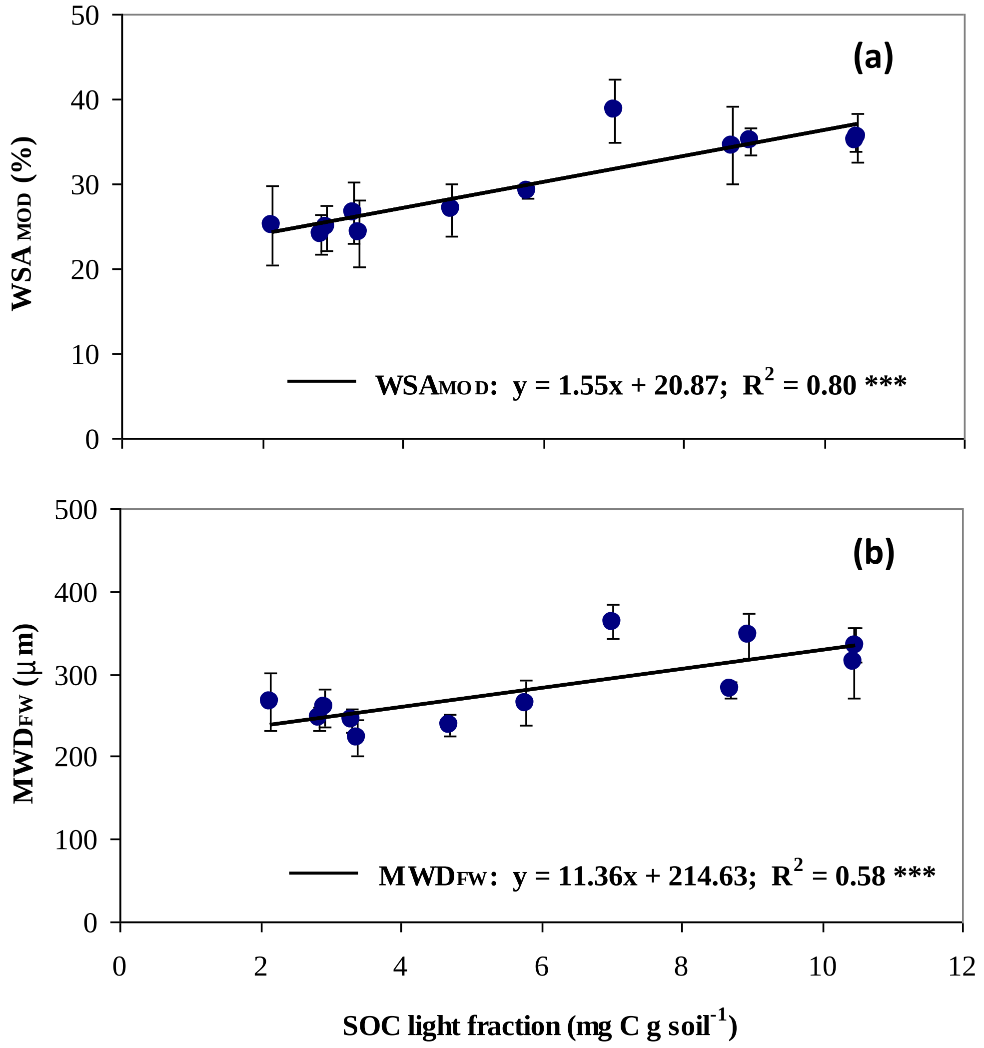

Figure 4-2. Relationship between soil organic carbon (SOC) light fraction and aggregate stability, (a) applying the modified water aggregate stability test (without pre-wetting, WSA_{MOD}) or (b) according to the mean weight diameter test after fast wetting (MWD_{FW}). Bars represent the standard error of four replicates, *** $p<0.001$.

The sum of total light SOC (from 0.05 up to 2 mm; Table 4-IV) was positively and significantly ($p<0.001$) correlated with the aggregate stability (Figures 4-2a and 4-2b), but the best adjustment was obtained with WSA_{MOD} ($R^2 = 0.80$).

Table 4-IV. Average values (n=3) of organic soil carbon from a bulk soil and from different physical sizes and density soil fractions, associated to different fertilization practices maintained during a period of 11 years in a maize crop. Light fraction was analysed according to the total volatile solids methodology. The oxidizable organic carbon by dichromate oxidation was analysed in the remaining samples.

	Fractions (mm)[‡]					**Total oxidizableC (dichromate)**[‡]
	0.2-2		**0.05-0.2**		**<0.05**	
Treatment[†]	**Heavy**	**Light**	**Heavy**	**Light**		
	------------------------------------- g C kg soil^{-1}					--------------------------
0-0	0.01	0.61C	0.59	2.33C	4.77B	7.27C
0-300MNF	0.01	0.93BC	0.64	2.56C	5.23B	7.90C
30DCM-0	0.01	1.96AB	1.24	5.28B	5.87B	11.80B
60DCM-0	0.01	2.17A	0.57	7.67A	8.07A	14.63A
Significance	NS	*	NS	***	*	***

NS: Not significant ($p>0.05$).

* Significant at the 0.05 probability level.

*** Significant at the 0.001 probability level.

[†] MNF: mineral nitrogen fertilizer applied as calcium ammonium nitrate (27 % N), the number behind indicates the applied rate of 300 kg N ha^{-1} yr^{-1}. DCM: dairy cattle manure, numbers behind indicate the average theoretical applied rate: 30 Mg ha^{-1} yr^{-1} or 60 Mg ha^{-1} yr^{-1}.

[‡] Mean values in a column followed by different letter are significantly different at the 0.05 probability level based on the Duncan Multiple Range Test.

The abundance of earthworms (Fig. 4-3) increased with DCM rates and in the 60DCM-0 treatment was significantly higher ($p<0.10$) than the control (0-0) or the MNF.

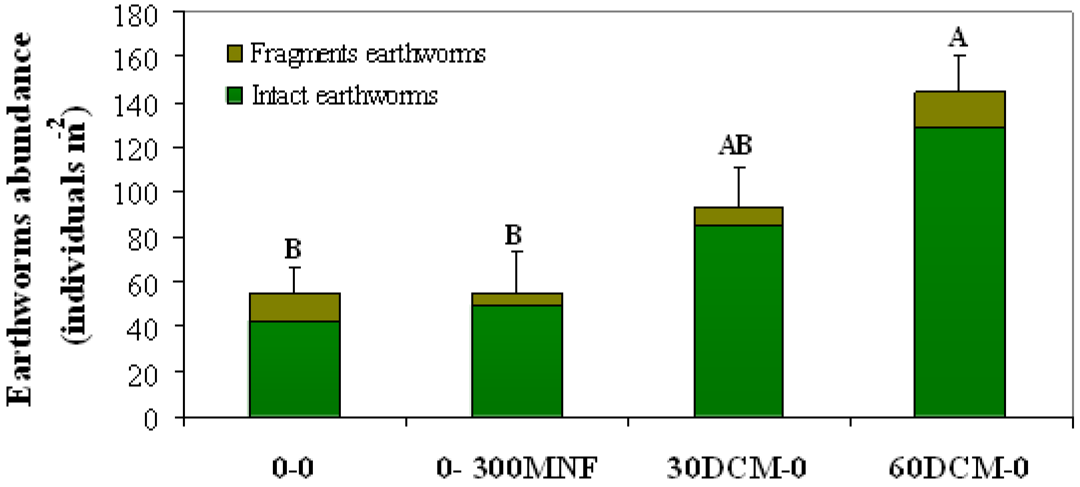

Figure 4-3. Earthworms abundance in each fertilization treatment: 0-0 or the control (no N, no manure applied); 0-300MNF: mineral N fertilizer (calcium ammonium nitrate, 27 % N) applied when six-eight leaves are visible and at rate of 300 kg N ha^{-1} yr^{-1}; 30DCM-0 and 60DCM-0: dairy cattle manure applied at wet-weight rate of 30 Mg ha^{-1} yr^{-1}, or 60 Mg ha^{-1} yr^{-1} at sowing. Mean values of abundance followed by a different letter are significantly different at the 0.10 probability level based on the Duncan Multiple Range Test. Bars represent the standard error of three replicates.

Porosity (apparent diameter >25 µm) accounted for 17.11 % to 22.63 % of the thin section area (Fig. 4-4), without significant differences between fertilizer treatments and the control, nor for the different pore sizes with the exception of the upper class (> 400 µm) which was lower in the control plots. Shape differences (Table 4-V) were present at pore ranges of 100-200µm (Solidity) and 200-400µm (Circularity and Solidity). MNF plots were more solid than in the control and in the 30DCM plots, as well as more circular. When looking to all sizes, pore circularity tended to decrease as pore size increased (Table 4-V). The opposite trend occurred in the aspect ratio.

Table 4-V. Average values (n=6) of different shape porosity parameters: Circularity (Circ.), Aspect Ratio (AR), and Solidity (S), for each fertilization treatment[†] and pore sizes.

Pore size	***Shape parameters***[‡]		
25-65 µm	**Circ.**	**AR**	**S**
0-0	0.947	1.497	0.876
0-300MNF	0.959	1.478	0.872
30DCM-0	0.906	1.703	0.856
60DCM-0	0.938	1.538	0.874
Significance	NS	NS	NS
65-100 µm	**Circ.**	**AR**	**S**
0-0	0.848	1.657	0.839
0-300MN[†]	0.874	1.593	0.855
30DCM-0	0.787	1.790	0.817
60DCM-0	0.810	1.767	0.841
Significance	NS	NS	NS
100-200 µm	**Circ.**	**AR**	**S**
0-0	0.688	1.772	0.808B
0-300MNF	0.735	1.888	0.845A
30DCM-0	0.643	1.935	0.787B
60DCM-0	0.645	1.972	0.820AB
Significance	NS	NS	S (0.02)
200-400 µm	**Circ.**	**AR**	**S**
0-0	0.477AB	2.088	0.734B
0-300MNF	0.556A	1.937	0.809A
30DCM-0	0.451B	2.083	0.721B
60DCM-0	0.449B	2.093	0.762AB
Significance	S (0.04)	NS	S (0.03)
> 400 µm	**Circ.**	**AR**	**S**
0-0	0.300	2.215	0.644
0-300MNF	0.354	2.120	0.747
30DCM-0	0.263	2.235	0.624
60DCM-0	0.266	2.110	0.686
Significance	NS	NS	NS

[†] MNF: mineral nitrogen fertilizer applied as calcium ammonium nitrate (27 % N); the number behind indicates the applied rate of 300 kg N ha^{-1} yr^{-1}.DCM: dairy cattle manure; numbers behind indicate the applied rate of 30 Mg ha^{-1} yr^{-1} or 60 Mg ha^{-1} yr^{-1}.

[‡] Mean values in a column followed by different letter are significantly different at the 0.05 probability level based on the Duncan Multiple Range Test.

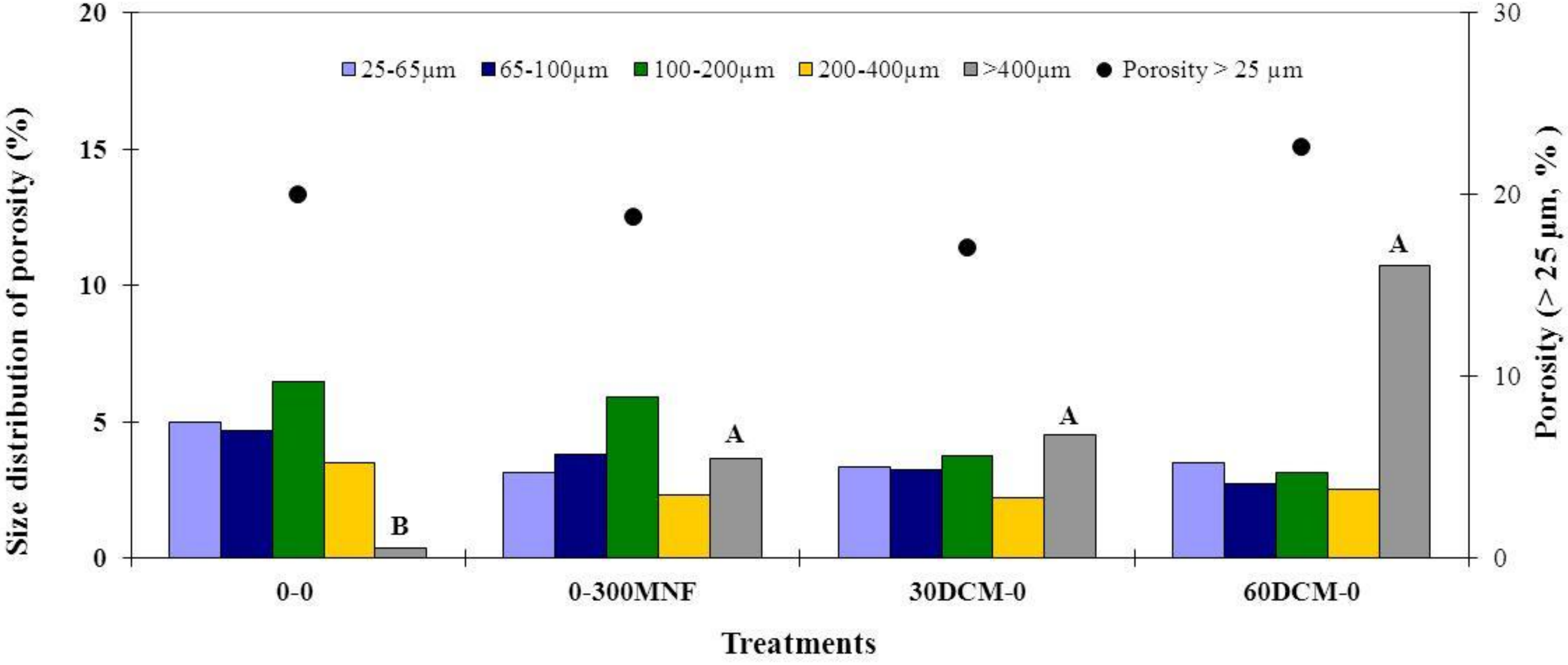

Figure 4-4. Average values (n=6) of the porosity area (apparent diameter > 25 µm) and its distribution for each fertilization treatment maintained in during a period of 11 years in a maize crop. The fertilization treatments were: 0-0 or the control (no N, no manure applied); 0-300MNF: mineral N fertilizer (calcium ammonium nitrate, 27 % N) applied at rate of 300 kg N ha^{-1} yr^{-1} when six-eight leaves were visible, and; 30DCM-0 and 60DCM-0: dairy cattle manure applied at wet-weight rate of 30 Mg ha^{-1} yr^{-1}, or 60 Mg ha^{-1} yr^{-1} at sowing. Mean values of abundance followed by a different letter were the only ones with significant difference at the 0.05 probability level based on the Duncan Multiple Range Test. Analysis were done with the values of transformed data ($x^{0.5}$). Bars represent the standard error of three replicates.

DISCUSSION

Soil aggregate stability

The significant increase of aggregate resistance against the slaking disaggregating effect, in DCM treatments (Table 4-III), was in agreement with findings of other authors about improvement in aggregate stability associated with long term cattle manure applications (Aoyama *et al*., 1999; Tripathi *et al*., 2014). Slaking is associated with a lack of organic bonding between particles (Ashman *et al*., 2003). These bonding agents can be temporary and transient, but in soils with low OM content (<10 g kg^{-1}) transient binding agents such as polysaccharides are the most important (Tisdall & Oades, 1982). The introduction of animal residues can stimulate microbial activity (Hernández *et al*., 2007) and consequently, the production of polysaccharides. The increase in aggregate stability due to manure addition has a supplementary value, because the particular soil's clay content is very low (Table 4-I). The importance of mineral components (lithology) on soil aggregate stability was pointed out by Cerdà (1996). Clay content and SOC associated with aggregates are the principal determinants of water stable aggregation (Boix-Fayos *et al*., 2001). Thus, low clay content aggregates are more vulnerable to disruptive forces compared with high clay content ones (Edwards & Bremner, 1967; Lehrsch *et al*., 1991). Aggregate stability improvements by manure addition would also result in better protection against water erosion, as aggregation increases infiltration and reduces runoff (Bronick & Lal, 2005; Arjmand Sajjadi & Mahmoodabadi, 2015).

Soil organic carbon

The carbon balance (manure *vs*. mineral fertilization) results in a positive value (Table 4-IV) for low rate manure (30DCM-0) which represents approximately 6.7 Mg C ha^{-1}, in the first 10 cm depth (as average value a bulk density of 1350 kg m^{-3} has been adopted). The increase of SOC content in manure treatments was mainly associated with the light SOC fraction, which increased by 107% or by 282% for 30DCM-0 and 60DCM-0 treatments respectively, when compared with MNF fertilization. Differences in the light fraction of SOC can be explained because it is a labile source of soil C and it is strongly influenced by factors related to the recent history of organic matter addition (Gosling *et al.*, 2013). Thus, it is sensitive to changes in management practices (Gregorich *et al*., 1997). Our results corroborate Leifeld & Kögel-Knabner (2005) statements saying that the light SOC fraction is an early indicator of future (long-term) impacts of management on soil quality. The importance of the SOC light fraction as a sensitive indicator of changes in OM status associated with fertilization practices was also observed by Bhogal *et al*. (2009) on annual manure additions (>7 years). Changes in the SOC light fraction linked to manure applications controlled the magnitude of changes in aggregate stability (Fig. 4-2a and 4-2b) although a small fraction could be associated with other temporary stabilizing materials, e.g. stover incorporation and roots, as can be seen for the mineral fertilizer treatment (Table 4-IV). This is the key point of our research which distinguishes it from works of others authors (Whalen & Chang, 2002; Hou *et al*., 2012; Tripathi *et al*., 2014; Gelaw *et al*., 2015; Mikha *et al*., 2015) where soil aggregation was related to total SOC. It also reinforces the warning of Pulido Moncada *et al*. (2015) when using the SOC as an estimator of aggregate stability, that specific fractions of the SOC can be the stabilizing agent as, in our case, the light fraction despite the increment of the most stable SOC fraction at the highest manure rate (Table 4-IV). The light fraction is considered to be the decomposing plant and manure part with a rapid turnover and low specific density (Whitbread, 2003), that stimulates polysaccharide production (transient binding agents) by microbial activity. The continued polysaccharide production will result in increments in the aggregate stability (Tisdall & Oades, 1982).

Total porosity, size classes and shape parameters

Fertilization, whatever is the nature of the fertilizers (minerals or manures), enhances the presence of pores (Fig. 4-4) in the upper size class (>400 µm) without modifying their shape (Table 4-V). This result is in accordance with Allison (1973) in the sense that aggregation improvement extends the volume of large pores. This fact is particularly relevant in this agricultural system as these pores favor aeration and soil water infiltration (Pagliari & Vignozzi, 2002) and, as a consequence, the runoff coefficient and the sediment transport capacity of water is reduced (Dosskey *et al.*, 2007). Compared with the results of Miller *et al.* (2002), no increase of macropores and mesopores (100-1000 µm) was observed as manure rates increased, although the tendency existed (Fig. 4-4).

The solidity parameter gives information about the irregularity, tortuosity and roughness of a pore. Also, circular pores are smooth pores, which tend to seal when soil is wet (Pagliari & Vignozzi, 2002). Then, the moderately irregular pores have walls which increase water retention capacity and superficial contact by capillarity. This behavior, enhanced by manure application at an agronomic rate (30DCM), is an environmentally positive aspect of manure use, despite its attenuation at a higher rate (60DCM).

Earthworms

Earthworms' abundance could have been underestimated in terms of anecic species as they can easily escape to deeper soil layers. For these ecotypes other different expulsion techniques are available (Valckx *et al.*, 2011). Nevertheless, some authors say (Bartlett *et al.*, 2006, 2010) that behavioral expulsion techniques overestimate anecic species in comparison to endogeic species. Besides, Murchie *et al.* (2015) found that the species which increased with the application of cattle slurry were epigeic earthworms; and to a lesser extent (just one species) endogeic earthworms, while anecic species were not affected. Thus, the hand sorting technique was a sensible option. Earthworm abundance tended to increase with manure rates (Fig. 4-3) but had no influence over macroporosity differences between fertilization treatments (mineral or manures), only when they were compared with the control (no N). As organic debris was similar in plots that received N fertilization, and the contribution of earthworms is the physical mixing of soil minerlas, water, microbes and residual matter, this fact could have been the reason for the absence of significant differences in soil macroporosity between all the fertilized plots (Fig. 4-4). Furthermore, the excretion from the gut releases organic materials which begin to form a structural fabric within the soil (Lee & Foster, 1991). Stable aggregates in soil are linked to the burrowing actions of earthworms (Ketterings *et al.*, 1997). Earthworms enhance the litter-derived C transfer into the soil profile (Novara *et al.*, 2015) and the incorporation of crop-derived C into macroaggregates and more importantly into microaggregates formed within macroaggregates (Pulleman *et al.*, 2005). The dominant mechanism for enhanced aggregate stability from excreted pellets is the generation of bonds of clay-polyvalent cation-organic matter linkages. Polysaccharides as well as other organic polymers are involved in the bonds described, and the differences between them (more or less anionic groups) will depend on the ingested materials (Shipitalo & Protz, 1989). At this point, the added manure could set up some differences in aggregation in comparison with to the mineral fertilized plot which just received plant residues. As a consequence, the relationship between the presence of the light organic matter fraction (greater amount in manured treatments; Table 4-IV) and aggregate stability (Fig. 4-2) could be enhanced by the activity of earthworms.

Management of the agricultural system

Manure application is a fertilization option in which a consideration of overall sustainability must be included: yield productivity, soil quality and overall nutrient management. In this intensively managed Mediterranean agricultural system, maize yields (15 to 18 Mg ha^{-1}) are considered high, whatever the fertilization option is (mineral or/and manures). Thus, the preservation of soil quality, as a decision factor when evaluating fertilization strategies, can be easily accepted by farmers.

Considering the yields attained (Table 4-II) and an average maize nutrient extraction for each 1000 kg of grain and hectare close to 28-30 kg N, 4.4-5.3 kg P and 19-21 kg K (Betrán-Aso, 2010), at the lowest DCM rates there could be a constraint on N availability depending upon mineralization values (i.e. residual effect). The applied phosphorus is close to crop needs, which justifies the addition of mineral P. This is a key point as surface application of manure often results in very high P concentrations at the soil surface (Andraski & Bundy, 2003), and P can be lost by sediment transport losses. Nevertheless, application of dairy manure with high solid content (210-280 g kg^{-1}) reduces sediment and particulate P losses in runoff (Yagüe *et al*., 2011). Our manure applications, with high dry matter content (304±68 g kg^{-1}), could also help in avoiding the transport of sediments and the consequent P runoff because they increase aggregate stability related to the usual slaking phenomena in Mediterranean conditions. For potassium, as the residues are incorporated, there is considerable K recycling, but also a need for complementary mineral fertilization. Furthermore, DCM tends to increase earthworm abundance and the solidity of some pores (200 to 400 µm) related with water infiltration which will result in a better water management efficiency.

CONCLUSIONS

Dairy cattle manure applied annually to maize favoured soil aggregate stability against the destabilizing effect of slaking on dry aggregates. These results were independent of the measurement procedures: WSA_{MOD} or MWD_{FW}. The improvement in aggregate stability was associated with increments in the SOC content, mainly in the light organic matter fraction. For a period of eleven years, the increment of SOC in manured plots: 30 or 60 Mg ha^{-1} applied, ranged from 3.9–4.9 g C kg soil^{-1} to 6.7–9.1 g C kg soil^{-1} respectively, when compared with mineral fertilization. The earthworm abundance increased with manure rates although it was not translated into an increment of the areas occupied by pores with an apparent diameter >25 µm. Changes in porosity by any fertilization treatment consisted in the increase of the upper fraction (>400 µm). In the interval from 100 up to 400 µm, the 30DCM treatment maintained a lower circularity and pore solidity than MNF. These changes in pore shape could be translated as a way to facilitate water infiltration and to avoid surface sealing. The annual use of manure in these agricultural systems, at low rates such as 30 Mg ha^{-1}, can be recommended because of the positive impacts on soil quality parameters and the achievement of high yields. Applying higher annual manure rates such as 60 Mg ha^{-1} is a more risky option for a long term sustainable management strategy (high nutrient addition in relation to the crop’s needs), as there may be groundwater water quality concerns (e.g. leaching of nitrates).

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5.- LONG TERM APPLICATION OF DAIRY CATTLE MANURE AND PIG SLURRY TO WINTER CEREALS IMPROVES SOIL QUALITY

Aquest apartat està basat en l’article:

LONG TERM APPLICATION OF DAIRY CATTLE MANURE AND PIG SLURRY TO WINTER CEREALS IMPROVES SOIL QUALITY

Francesc Domingo-Olivé, Àngela D. Bosch-Serra, María R. Yagüe, Rosa M. Poch and Jaume Boixadera

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Nutrient Cycling in Agroecosystems

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ABSTRACT

Organic fertilizers (manures and slurries) applied repeatedly over many cropping seasons favourably influence nutrient recycling, maintenance of soil organic matter (SOM), and improve soil quality parameters such as soil aggregation and porosity. These aspects are particularly relevant in Mediterranean environments characterized by low SOM. This study was set up in a subhumid Mediterranean area where two different trials, devoted to winter cereals, were fertilized with dairy cattle manure (DCM) or pig slurry (PS) for a period of 12 years. One objective of this research was to evaluate the impacts of these fertilization practices on aggregate stability and SOM fractions, when compared with a mineral N fertilizer and a control (no-N) treatment. Porosity and pore shape were also studied in PS plots. The use of DCM significantly increased water stable aggregates by up to 16.4 % - 18.0 %. Slurry addition did not affect aggregation but it increased the area occupied by pores >65µm. Soil organic carbon (SOC) and light organic fraction (0.05-0.2mm) increased with DCM incorporation but in PS treatments the SOC increment was non-significant. Data from DCM and PS together showed a positive and significant linear relationship between SOC ($p<0.05$, $R^2=0.60$), SOC light fraction ($p<0.01$, $R^2=0.75$) and SOC light fraction at 0.05-0.2 mm size ($p<0.01$, $R^2=0.83$), with water-stable aggregate. The use of animal residues (DCM or PS), applied according to an N criterion, increased available phosphorus and potassium soil content while improving yields. The enrichment of soil nutrients with DCM and PS requires further research in order to avoid potential environmental impacts.

Keywords: aggregate stability; organic carbon fractions; nutrient balance; slaking; soil porosity; pore size distribution; Mediterranean conditions; organic fertilizers

INTRODUCTION

Soil amendment with organic fertilizers of animal origin is a common practice in order to improve soil fertility and productivity, particularly in agroecosystems with naturally low organic matter content which are very susceptible to soil degradation. The improvement of management practices to maintain or even to increase soil organic carbon (SOC) is of great interest as SOC losses are a hazard to soil quality and productivity (Jones *et al*., 2012). Pig (*Sus scrofa domesticus*) slurry (PS) is rich in N, and ammonium-N accounts for around 75 % of it (Yagüe *et al*., 2012a). It also has a low organic carbon content (C:N ratio ranges between 4 to 8) in contrast to solid dairy cattle (*Bos taurus*) manure (DCM) (C:N ranges between 10 to 25). These organic materials are also quite different in terms of dry matter (DM) and N forms which may have different influences on microbial activity and chemical changes in soil (Ndayegame and Cotê, 1989; Velthof *et al*., 2000). When organic residues with a low C:N ratio are incorporated into soil, microorganisms have sufficient N for protein metabolism but not enough C as an energy source. Then, the microbial oxidation of native soil organic matter will occur (Trolldenier, 1975). Other studies suggest that a C:N ratio of manures greater than 15-19 results in net N immobilization (Van Kessel *et al*., 2000; Calderon *et al*., 2005), which affects its crop availability. Nevertheless, soil chemical alterations that occur due to manure incorporation are strongly influenced by soil texture, precipitation, quantity of manure applied and time between application and sampling (Choudhary *et al*., 1996).

The most common criterion used in trials on organic fertilizers is how well they substitute for N mineral fertilizers. Other aspects, such as the improvement of soil physical properties, are very frequently neglected. Long term effects of fertilization practices on aggregate stability and soil organic carbon have been studied. However, few articles have focused on aggregate stability according to the nature of the organic matter applied (Whalen and Chang, 2002; Yagüe *et al*., 2012b; Wang *et al*., 2014).

Soil aggregate stability is important for several ecosystem functions, such as water infiltration, reduction of erodibility and runoff, aeration for plant growth (Kemper and Rosenau, 1986), and physical protection of soil organic matter (SOM) (Tisdall and Oades, 1982). Disintegration of macroaggregates by “slaking” associated with the fast wetting process caused by penetration of water into soil dry aggregates, is the main destabilizing factor in rainfed soils (i.e. dry bare soil) in Mediterranean conditions. Dairy manure fertilization can improve soil aggregate stability against slaking also it controls dissolution and dispersive actions (Nyamangara *et al.*, 1999; Paré *et al.*, 1999). As soil structure is the combination of different types of pores with solid particles (aggregates), characterization of the pore system is also an interesting because many physical properties which are relevant in agronomic functions, are determined by the size distribution and shape of pores (Pagliai and Antisari, 1993).

In rainfed Mediterranean conditions, it is not well known how the long-term management of organic fertilizers affects soil quality parameters, particularly in terms of organic carbon fractions (heavy and light fraction), aggregate stability (mainly regarding the slaking disaggregation process) and porosity. Furthermore, only long-term experiments allow the required precision in the evaluation of changes in soil quality and their impacts on crop productivity (Peterson *et al.*, 2012). A recent meta-analysis by Maillard and Angers (2014) on manure application and SOC stocks emphasized the need to further investigate the long-term impact of manure according its characteristics in relation to the animal species of origin.

Soil organic matter is considered the primary binding agent responsible for improving aggregate stability in microaggregates (<250 µm) and macroaggregates (>250 µm) (Tisdall and Oades, 1982). The light fraction of SOM is sensitive to changes in management practice (Bremer *et al.*, 1994) and it is considered to represent an early indicator for determining the long term impacts of management techniques on soil quality (Leifeld and Kögel-Kabner, 2005). Shukla *et al.* (2006) concluded that if only one soil attribute is used for monitoring soil quality changes every 3-5 years, SOC should be selected.

Organic fertilizer is usually applied to cover crop N needs. This criterion can enhance soil P build-up. Much of this phosphorus is bound in soil in less available forms, but some may be lost to the environment where it can contribute to the eutrophication of water bodies (Toth *et al*., 2006). This occurs because the N:P ratio in manure is narrower than the N:P ratio of nutrient demand by most crops.

Site-specific optimization of soil performance is included in the criteria for sustainable soil-use, a forefront of the agricultural policies in the European Union, framed by the thematic strategy for soil protection and ongoing activities. The EU trend is to widen research on factors such as land use, preservation of SOM and more efficient use of resources such as manure (COM 2012). The evaluation of soil quality and soil-use sustainability should support the synergies between local soil-use practices and regulatory conditions, land use and policy planning (Tóth *et al*., 2007). The appraisal of these soil-use fertilization practices must be done on a long-time scale.

Long-term experiments were initiated in a subhumid rainfed Mediterranean area of NE Spain in order to monitor the effects of organic (manure and slurry) and mineral fertilizers on crop productivity. We hypothesized that manure and even PS with low OM content may improve soil quality. The parameters chosen for study were aggregate stability, organic matter fractions (heavy and light) and soil fertility. In PS plots, due to the low OM content of slurries, preliminary research on porosity was done through thin section methodology. The selected fertilization practices to be studied were associated with the highest yields and the accomplishment of the EU nitrate directives (European Union, 1991) in the area. At the start of the experiment, the maximum amount of N applied in organic fertilizers was 210 kg N ha^{-1} yr^{-1}, but later it was reduced to 170 kg N ha^{-1} yr^{-1} (Generalitat de Catalunya, 2009a). The chosen treatments were evaluated after 12 years of DCM or PS incorporation in each cropping season.

MATERIALS AND METHODS

Soil and climate description

The experiments were established in 2001 (La Tallada d'Empordà, Girona, NE Spain). The altitude of the site is 17 m a.s.l. and coordinates are 42° 03' 15" N, 03° 03' 46" E. The soil is very deep (>1.2 m), well drained, non-saline, calcareous and without pebbles. Soil bulk density was 1565 kg m^{-3} for the first 0.30 m and 1700 kg m^{-3} from 0.30 to 0.90 m depth. Water holding capacity was 176 mm (0-0.90 m). In the upper layer (0-0.30 m) soil texture is loamy and the SOM content is about 17 g kg^{-1} (10 g SOC kg^{-1}). It decreases with depth down to 7 g kg^{-1} (Table 5-1). The soil is classified as an Oxyaquic Xerofluvent (Soil Survey Staff, 1999). The field has a gentle slope, so that the aquic character (saturation of the surface in most years) was more relevant in the bottom part of the field.

Table 5-1. Physical and chemical characteristics of the soil, in the field trial. Composite samples (0-0.30m, 0.30-0.60m and 0.60-0.90m) were obtained at the start of the fertilization experiment (October 2001).

	Depth (m)		
Parameter	**0-0.3**	**0.3-0.6**	**0.6-0.9**
Particle size distribution (g kg^{-1})†			
Sand (2000 <Ø< 50 µm)	458	412	538
Silt (50 <Ø< 2 µm)	413	465	351
Clay (Ø < 2 µm)	129	123	111
pH (water; 1:2.5‡)	8.4	8.4	8.2
Electrical conductivity (1:5‡; dS m^{-1}, 25ºC)	0.13	0.18	0.22
Organic matter (g kg^{-1})	17	14	7
Total N (g kg^{-1}; Kjeldahl)	0.10	0.08	0.05
Phosphorus (mg P kg^{-1}; Olsen)	32	14	7
Potassium (mg K kg^{-1}; NH_4OAc, 1N, pH=7)	306	180	89
Calcium carbonate equivalent (g kg^{-1})	12.9	12.3	11

† Ø: particle apparent diameter.

‡ Relation of soil: distilled water.

The area has a dry Mediterranean climate according to Papadakis classification (MAPA, 1989). The annual average temperature is 15.8 °C and summer temperatures are high (on average 23.0 °C). Average annual precipitation is 602 mm. Potential evapotranspiration is also high, based on Thornthwaite's equation (~827 mm yr^{-1}). Most rain falls in autumn with important storm events in September-October-November which can cause runoff if the soil is bare (Fig. 5-S1).

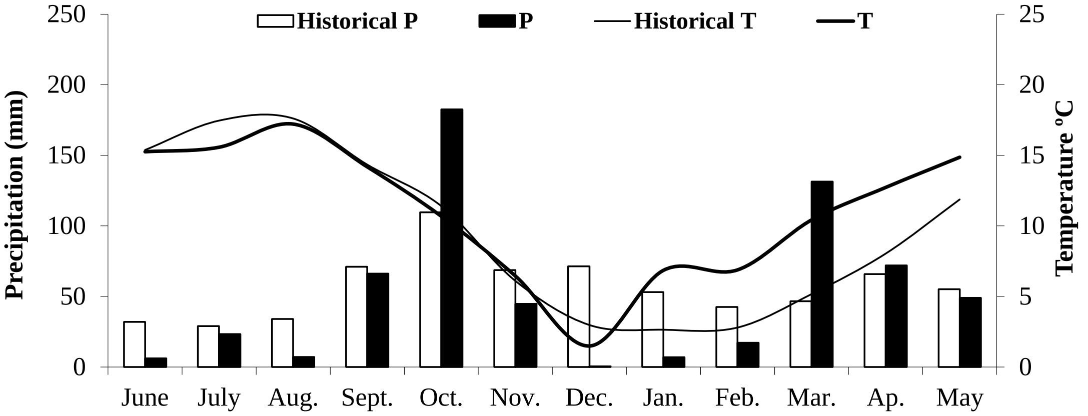

Figure 5-S1: Monthly precipitation (P) and mean air temperature (T) during the crop season samplings (2012-2013) and for the historical period (1993-2014).

Description of the experiment

The experimental field was cropped with a rotation of wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) during the experimental period 2001/02 to 2012/13. The standard rotation was wheat-barley-barley. The field was annually sown in November-December and harvested in late June-early July. During each cropping season, conventional tillage management (main tillage with mouldboard plough or disc-harrow between 0.20-0.25 cm depth) were employed. The straw was removed from fields according to farmers' practice. The stubble was incorporated during summer time.

Two experimental trials were established in the same field. The experiment with cattle manure (DCM) was located in the upper part of the field and the experiment with pig slurry (PS) was located at the bottom. Both locations were representative of soil conditions in the area. In both trials DCM and PS were applied before sowing. The trials included treatments with mineral N fertilization (MF) at sidedressing. Treatments in the DCM trial consisted of a control (named 0-0$_{DCM}$; no-N addition), mineral N rate of 40 kg N ha^{-1} applied at sidedressing (named 0-MF$_{DCM}$), DCM treatments at presowing (DCM-0) only or combined with a mineral N sidedressing (40 kg N ha^{-1}; DCM-MF$_{DCM}$). In the PS trial treatments consisted of a control (named 0-0$_{PS}$; no-N addition), a mineral N rate of 50 kg N ha^{-1} applied at sidedressing (named 0-MF$_{PS}$) and PS treatments at presowing (PS-0) only or combined with mineral N applications as sidedressing (50 kg N ha^{-1}; PS-MF$_{PS}$). The average values of main chemical parameters of DCM and PS are described in Table 5-S1.

Table 5-S1: Main physicochemical average values (±standard deviation)[†] of dairy cattle manure (DCM) and slurry from fattening pigs (PS) in the period from 2001 to 2013.

Parameter	**DCM**	**PS**
Dry matter (%)	29.6 ±8.6	6.2 ±2.9
Organic matter (% dm)	59.3 ± 9.8	59.6 ± 9.4
Kjeldahl-N (% dm)	2.4 ± 0.4	2.4 ± 0.3
Ammonium-N (% dm)	0.4 ± 0.1	6.0 ± 6.5
Total N (% dm)	2.8 ± 0.5	8.4 ± 6.7
Phosphorus (P; % dm)	0.8 ± 0.2	2.8 ± 0.8
Potassium (K, % dm)	3.2 ± 1.0	4.9 ± 5.5
Ratio C:N	12.2 ± 0.9	6.1 ± 3.9

[†] % dm: expressed on a dry matter basis.

In each plot, rates of animal residues were adjusted by weighing the manure and the slurry applied. The average annually applied rate was 22.5±8.0 t ha^{-1} (±SD) in the DCM trial, which equaled a total average of N applied of 189±101 kg N ha^{-1}. In the PS trial, the average slurry rate was 47.3±13.7 t ha^{-1}, which equaled a total average of N applied of 187±108 kg N ha^{-1}. The average values of total N applied were between the limits of 170 to 210 kg N ha^{-1} yr^{-1}. At the start of the experiment the area was included in a non-vulnerable zone. Thus, 210 kg N ha^{-1} yr^{-1} was the advised upper threshold from N of organic origin. Later on, the area was included in a “nitrate vulnerable zone” and 170 kg N ha^{-1} yr^{-1} was the new upper threshold when using livestock residues (Generalitat de Catalunya, 2009b). In plots where PS was applied, the amount of 37.5 kg K ha^{-1} yr^{-1}, as potassium sulphate (50 % K_2O) was added because of the low K content of PS (Table 5-S1).

At sowing, the controls (0-0_{DCM} and 0-0_{PS}) and the mineral N fertilizer treatments (0-MF_{DCM} and 0-MF_{PS}) received phosphorus as calcium superphosphate (18 % P_2O_5). The amount of P applied was equivalent to 34.9 kg P ha^{-1} yr^{-1} in the DCM and PS experiments. They also received potassium as potassium sulphate (50 % K_2O) at a rate equivalent to 120.8 kg K ha^{-1} yr^{-1}.

Plot size was 48 m^2 (6 m wide and 8 m long) in DCM trial and 30 m^2 (3 m wide and 10 m long) in the PS trial. The treatments in each trial were arranged according to a randomized block design with three replicates.

Characteristics of the manures and the slurries applied

Every cropping season, in the field, just before fertilizer application, a composite sample of PS and DCM from each trial was taken. The samples were analysed in the laboratory. The analytical methods used were gravimetric dry matter content at 105 ºC, organic matter by ignition at 550ºC, organic nitrogen by the Kjeldahl method, ammonium nitrogen by distillation and titration according to methods 4500-NH_3 B-C ALPHA (2012). Total phosphorus and potassium were analysed by acid digestion (wet) and further determined using inductively coupled plasma atomic emission spectroscopy (USEPA, 1992).

Soil porosity and pore-size distribution and shape in PS trial

In the PS trial, in order to study the effect of small amounts of OM additions on soil porosity (> 25µm) and pore shape, undisturbed soil was sampled on December 5th 2011 (≈ 13 months after the last presowing fertilization). Treatments 0-MF_{PS}, PS-0 and PS-MF_{PS} were sampled.

For each treatment, three undisturbed samples (0-10 cm depth) were obtained, one from each block. They were dried at room temperature and impregnated with polyester resin with a fluorescent dye (Uviex©). One vertical thin section (5 cm wide x 13 cm long) was made from each block.

From each thin section, three fields 42.0 x 31.5 mm were selected for obtaining images, in three light conditions: parallel polarisers (PPL), crossed polarisers (XPL) and incident UV light. The latter was processed with ImageJ (Rasband, 2008) to obtain digital binary images from which the total porosity, associated with pores with an apparent diameter (AD) > 25 µm (the minimum threshold allowed by the procedure) was statistically analysed. Each image set was used to perform a pore-size distribution analysis based on an "opening" algorithm of mathematical morphology using the Quantim4 library (Vogel, 2008). The area occupied by pores was divided into four ranges according to the pores' AD: 25-65 µm; 65-100 µm, 100-200 µm, 200-400 µm, > 400 µm. Images were analysed and four shape descriptors, defined in Ferreira and Rasband (2012) were determined: Circularity (Circ.), Aspect Ratio (AR), Roundness (Round) and Solidity (S).

Soil aggregate stability, organic matter fractionation and other chemical analysis

The preliminary results (5th December 2011 sampling) showed differences in soil porosity associated with PS addition. This fact justified a new sampling. Thus, soil was sampled after harvest (July 2013), and DCM extended treatments were included for aggregate stability and SOC fractionation.

Soil was sampled on July 23th of 2013 after cereal harvest (≈ 9 months after last presowing fertilization with organics). Samples were taken from 0-10 cm depth for each treatment and each replication in the three field blocks. Selected treatments were: $0\text{-}0_{DCM}$, $0\text{-}MF_{DCM}$; DCM-0, and $DCM\text{-}MF_{DCM}$ from the DCM trial and $0\text{-}0_{PS}$, $0\text{-}MF_{PS}$, PS-0, $PS\text{-}MF_{PS}$ from the PS trial (Table 5-2).

In these samples, SOC fractionation and main chemical parameters (EC, pH, N, P, and K) were analyzed. In addition to this, two aggregate stability tests, named mean weight diameter (MWD) and water-stable aggregates (WSA), were applied. The first allowed aggregate-size distribution evaluation after a fast wetting. The MWD was obtained following Le Bissonnais (1990) and the further modification established by Amézqueta *et al*. (1996). It was expressed in microns (µm) as the sum of four multiplications. Each multiplication was obtained as a product of the relative mass percentage of four size aggregate classes (<250 µm, ≥250 µm to 500 µm; ≥500 µm to 1000 µm; ≥1000 µm to 2000 µm) and the associated mean diameter of aggregates in each class (125 µm, 375 µm, 750 µm and 1500 µm).

In the second aggregate stability test, the WSA methodology followed Kemper and Rosenau (1986) with the exception of the initial gentle pre-wetting of aggregates which was avoided, as some authors recommend (Pulido-Moncada *et al*., 2013). In our case, it was avoided in order to focus on the slaking disaggregation effect which predominates under Mediterranean rainfed conditions. Four laboratory replicates were used for each sample and WSA was expressed as a mass percentage, discounting the mass associated with sand.

For each fertilization treatment, five soil density (light and heavy) and physical (<0.05 mm, ≥0.05-0.2 mm and ≥0.2-2 mm) fraction OM sizes were obtained according to the procedure NF X 31-516 established by AFNOR (2007). The SOC from the light fraction was analysed following the total volatile solids (TVS) methodology. The oxidizable SOC from the heavy fraction was determined by dichromate oxidation and subsequent titration with ferrous ammonium sulphate (Yeomans and Bremner, 1988).

The other analysed chemical parameters were pH (potentiometry; 1:2.5 soil:distilled water), electrical conductivity at 25 ºC (1:5 soil:distilled water), available P (Olsen method) and available K (ammonium acetate 1N, pH=7), following MAPA (1984).

Table 5-2. Averages[†] of total N, organic N and organic matter (OM) applied annually in dairy cattle manure (DCM) and pig slurry (PS) trials, where mineral N (MF) as a fertilization treatment was included at sidedressing (SideD). Grain yields (13 % humidity) of 2012-2013 sampling season are also presented.

Trial	**Treatments**[‡]	**Fertilizer treatment**		**Total N applied**	**MF**	**DCM or PS**[+]			**Grain yield. Harvest 2013**
		Sowing	**SideD**			**Org-N**	**NH_4^+N**	**OM**	
				kg N ha^{-1}		-------------------- **kg ha^{-1}**		-------------------	**(kg ha^{-1})[#]**
DCM	**0-0$_{DCM}$**	0	0	0	0	0	0	0	5531B
	0-MF$_{DCM}$	0	MF	40	40	0	0	0	5443B
	DCM-0	DCM	0	189	0	163 (±92)	26 (±13)	3897 (±1875)	7269A
	DCM-MF$_{DCM}$	DCM	MF	229	40	163 (±92)	26 (±13)	3897 (±1875)	7603A
	Significance								*
PS	**0-0$_{PS}$**	0	0	0	0	0	0	0	2382B
	0-MF$_{PS}$	0	MF	50	50	0	0	0	3447B
	PS-0	PS	0	187	0	71 (±46)	116 (±66)	1913 (±1694)	6262A
	PS-MF$_{PS}$	PS	MF	237	50	71 (±46)	116 (±66)	1913 (±1694)	6457A
	Significance								***

[†] Numbers in brackets are the standard deviation.

[‡] MF$_{DCM}$ and MF$_{PS}$: mineral N fertilizer, applied at a rate of 40 or 50 kg N ha^{-1} yr^{-1}, respectively, as calcium ammonium nitrate (27 %) at sidedressing; DCM and PS: dairy cattle manure and pig slurry applied just before sowing at an average rate of 22.5 or 47.3 t ha^{-1}, respectively.

[#] For yields, means followed by the same letter are not significantly different according to Duncan's Multiple Range Test (p=0.05).

* $p<0.05$, *** $p<0.001$.

Data analysis

All statistical analyses were performed using the SAS V8 (SAS Institute, 1999-2001) statistical software. When differences, according to the analyses of variance (ANOVA) were considered significant ($p<0.05$), Duncan’s Multiple Range Test (DMRT) was computed for comparing all possible pairs of means at the 0.05 probability level. Total porosity and pore shape data were normalized using the square root transformation. Soil carbon fractions and aggregate stability results were an exception, for which a threshold of $p<0.10$ was adopted in ANOVA analyses. For regressions, fit was considered acceptable if the coefficient of determination (R^2) was 0.75 or higher.

RESULTS AND DISCUSSION

After 12 years with similar fertilization schedules, plant yields justified the use of manures (Table 5-2) but the sidedressing with MF did not add a significant yield increase. The residual effects during the crop season causes the savings in fertilizer sidedressing (Schröder et al., 2005). The DCM trial attained better agronomic conditions than the PS trial, as is reflected by the high yields (>5.5 t ha^{-1}) achieved in the DCM control without N applied (Table 5-2).

Total porosity, size classes and shape parameters

After 10 years of annual addition of PS, the soil samples obtained in December 2011 (≈ 12-13 months after last application) did not show differences between MF and PS treatments in porosity associated with pores of apparent diameter higher than 0.25 µm (Table 5-3). However, in the 65 and 400 µm range, porosity was significantly higher in PS treatments than in the MF one (Table 5-3). The opposite was detected for pores larger than 400 µm. Pagliai and Antisari (1993) found similar results with a higher PS addition (100-300 m^3 ha^{-1} yr^{-1}). In their study, slurry resulted in increased porosity in the range of 50-500 µm compared with the control. The detected porosity changes in our experiment are relevant because pores in the range from 65 to 400 µm are transmission pores associated to aggregate packing. They are important for water flow during drainage, and moreover, they are the pores needed by roots to grow into (Greenland, 1977). The higher percentage of pores bigger than 400 µm in the MF treatment indicates the presence of small planar voids or fissures that separate larger aggregates.

As the addition of OM improves aggregate stability, as well as soil porosity (Pagliai and Antisari, 1993; Pagliai *et al.*, 2004), our findings on porosity suggest a potential effect of PS on aggregate stability despite the low OM addition. Thus, it was justified to go deeper into the potential influence of PS on physical properties such as aggregate stability. Shape parameters were not affected by fertilization treatments (Table 5-S2).

Table 5-3. Average values[†] (n=6) of total porosity (>25µm) and different porosity fractions, for each fertilization treatment, in pig slurry trial. Soil was sampled the 5th December 2011.

Treatment	**Total Porosity**	**Size porosity** (%)[#]				
Sowing-sidedressing[‡]	**> 25 µm**	**25-65µm**	**65-100µm**	**100-200µm**	**200-400µm**	**>400µm**
0-MF$_{\text{PS}}$	31.9	1.40 (0.12)	1.95 (0.14)B	4.33 (0.21)B	7.01 (0.27)B	17.20 (0.41)A
PS-0	31.7	2.35 (0.15)	3.33 (0.18)A	7.51 (0.27)A	9.60 (0.31)A	8.91 (0.28)B
PS-MF$_{\text{PS}}$	30.9	2.01 (0.14)	2.77 (0.17)A	6.78 (0.26)A	9.32 (0.30)A	10.07 (0.41)B
Significance	NS	NS	**	***	**	**

NS: no significant, p>0.05.; ** p<0.01; *** p<0.001

[†] Numbers between parenthesis indicate the transformed values [x^(1/2)] of porosity.

[‡] MF$_{\text{PS}}$: mineral nitrogen fertilizer, applied at a rate of 50 kg N ha^{-1} yr^{-1} as calcium ammonium nitrate (27%) at sidedressing; PS: pig slurry applied just before sowing at an average rate of 47.3 t ha^{-1}.

[#] Within columns, means followed by the different letter are significantly different according to Duncan Multiple Range Test at the α=0.05 level of significance.

Soil organic carbon fractions, soil aggregate stability and their relationships

After 12 years of annual DCM application, our results show a net increase of SOC by DCM addition (average increment value of 42 %) which equaled an increase of 4.5 g C kg^{-1} soil, when compared with the control and MF treatments (Table 5-4). The SOC light fraction at the 0.05-0.2 mm size was that most affected (p=0.055; Table 5-4). In PS treatments, the SOC tend to increase although only the PS-0 treatment was significantly different from the mineral (0-MF$_{\text{PS}}$ treatment) treatment (Table 5-4). These results can be explained by the low OM addition in PS compared with DCM (Table 5-S1 and Table 5-2) and the fact that straw was removed in all treatments. Thus, in our PS experiment, the effect is due to direct C input by the slurry itself. We consider the indirect C input through increased net primary production (including roots and crop residues) stressed by different authors (Whalen and Chang, 2002; Maillard and Angers, 2014) to be less important.

Table 5-S2. Average values (n=6), for different apparent pore diameter intervals, of porosity shape parameters: Circularity (Circ.), Aspect Ratio (AR), Roundness (Round) and Solidity (S). Samples were obtained the 5th December 2011 for each fertilization treatment of the pig slurry trial.

25-65 µm	**Circ.**	**AR**	**Round**	**S**
0-MF$_{PS}$	0.89	1.77	0.63	0.85
PS-0	0.91	1.70	0.66	0.86
PS-MF$_{PS}$	0.89	1.79	0.62	0.85
Significance	NS	NS	NS	NS
65-100 µm	**Circ.**	**AR**	**Round**	**S**
0-MF$_{PS}$	0.72	1.97	0.57	0.79
PS-0	0.75	1.90	0.58	0.80
PS-MF$_{PS}$	0.71	1.95	0.57	0.78
Significance	NS	NS	NS	NS
100-200 µm	**Circ.**	**AR**	**Round**	**S**
0-MF$_{PS}$	0.61	2.07	0.55	0.78
PS-0	0.62	2.06	0.54	0.77
PS-MF$_{PS}$	0.58	2.05	0.55	0.76
Significance	NS	NS	NS	NS
200-400 µm	**Circ.**	**AR**	**Round**	**S**
0-MF$_{PS}$	0.48	2.25	0.52	0.73
PS-0	0.48	2.16	0.54	0.73
PS-MF$_{PS}$	0.44	2.24	0.51	0.70
Significance	NS	NS	NS	NS
> 400 µm	**Circ.**	**AR**	**Round**	**S**
0-MF$_{PS}$	0.28	2.33	0.50	0.62
PS-0	0.28	2.21	0.52	0.61
PS-MF$_{PS}$	0.26	2.15	0.53	0.60
Significance	NS	NS	NS	NS

NS: non significant, p>0.05.

[†] MF$_{PS}$: mineral nitrogen fertilizer, applied at a rate of 50 kg N ha^{-1} yr^{-1} as calcium ammonium nitrate (27 % N) at sidedressing; PS: pig slurry applied just before sowing at an average rate of 47.3 t ha^{-1}.

Table 5-4. Average values[†] (n=3) of soil carbon in different physical sizes and density fractions and total oxidizable organic carbon by dichromate oxidation. Values were obtained from dairy cattle manure (DCM) and pig slurry (PS) trials maintained for a period of 12 years. Sampling was done at cereal harvest on the 23rd July of 2013.

		Fractions (mm)					**Total C**
		0.2-2		**0.05-0.2**		**<0.05**	
Trials	**Treatment**[‡]	**Heavy**	**Light**	**Heavy**	**Light**		
		---------------------------- g C kg soil^{-1} ----------------------------					
DCM	**0-0**$_{DCM}$	0.03	0.86	0.57	3.77B	5.34BC	10.58B
	0-MF$_{DCM}$	0.07	1.06	0.48	4.66AB	4.77C	11.05B
	DCM-0	0.06	2.02	0.79	6.14A	6.05AB	15.06A
	DCM-MF$_{DCM}$	0.05	2.37	0.74	5.69A	6.83A	15.69A
	Significance	NS	NS	NS	*	**	***
PS	**0-0**$_{PS}$	0.08	1.12	0.33	2.82	6.24	10.59B
	0-MF$_{PS}$	0.17	1.33	0.36	2.29	5.55	9.72B
	PS-0	0.22	2.21	0.45	3.66	6.09	12.63A
	PS-MF$_{PS}$	0.08	1.39	0.47	3.16	5.83	10.93AB
	Significance	NS	NS	NS	NS	NS	*

NS: not significant ($p>0.05$); *$p<0.05$, ** $p<0.01$, *** $p<0.001$.

[†] Within columns, means having a common letter are not significantly different according to DMRT at the α=0.05 level of significance.

[‡] MF$_{DCM}$ and MF$_{PS}$: mineral N fertilizer, applied at a rate of 40 or 50 kg N ha^{-1} yr^{-1}, respectively, as calcium ammonium nitrate (27 % N) at sidedressing; DCM and PS: dairy cattle manure and pig slurry applied just before sowing at an average rate of 22.5 or 47.3 t ha^{-1}, respectively.

The light fraction size of 0.2-0.05 mm represented between 36 to 42 % SOC in the DCM trial and between 23 to 29 % of the SOC in PS trial. This indicates that this fraction is an early indicator of SOC changes in soil (Leifeld and Kögel-Kabner, 2005). This higher significance on SOC changes after DCM application is consistent with the idea that its organic matter is more stable than that from PS (Velthof *et al.*, 2000). Also, due to the low C:N ratio of PS, the mineralization of its OM is faster. This makes it rather difficult to observe changes in the light fraction OM pool nine months after PS application. Time of sampling is a factor in detecting changes in soil chemical composition, as stated by (Choudhary *et al.* 1996), mainly because residues with low C:N ratio only have a temporary effect (Yagüe *et al.*, 2012b).

Table 5-5. Average values[†] (n=4) of the mean weight diameter after a fast wetting (MWD) and the mass percentage of water-stable aggregates (WSA) for both trials. Sampling was done at cereal harvest on the 23rd July of 2013.

Trial	Treatment	MWD (µm)	WSA (%)
Dairy Cattle Manure (DCM)	**0-0$_{DCM}$**	288	14.70C
	0-MF$_{DCM}$	321	15.00C
	DCM-0	307	18.31A
	DCM-MF$_{DCM}$	303	16.37B
	Significance	NS	***
Pig Slurry (PS)	**0-0$_{PS}$**	326B	11.93B
	0-MF$_{PS}$	341AB	13.53A
	PS-0	346AB	13.66A
	PS-MF$_{PS}$	363A	12.43AB
	Significance	*	NS

NS: not significant (p>0.05); Significant: *p<0.05, ***p<0.001.

[†] Within columns, means having a common letter are not significantly different according to DMRT (α=0.05).

[‡] MF$_{DCM}$ and MF$_{PS}$: mineral N fertilizer, applied at a rate of 40 or 50 kg N ha^{-1} yr^{-1}, respectively, as calcium ammonium nitrate (27 % N) at sidedressing; DCM and PS: dairy cattle manure and pig slurry applied just before sowing at an average rate of 22.5 or 47.3 t ha^{-1}, respectively.

The resistance of aggregates against the slaking effect, assessed by means of WSA, was significantly improved in DCM treatments when comparing with that of mineral fertilization or the control (Table 5-5). These results are in accordance with Paré *et al.* (1999) who found that the application of DCM for a three year period resulted in the production of cementing agents. These agents stabilized aggregates against slaking forces independently of the tillage system (conventional tillage or no-tillage). In the pig slurry trial, differences were found when stability was evaluated by means of MWD. The MWDs tended to increase as the amount of applied N increased, independently of its origin (Table 5-5).

The MWD was a better indicator of stability in PS trials than WSA because PS enhances the presence of aggregates in the intervals between 250 and 500 µm and from 500 to 1000 µm (Figure 5-1). Also because the addition of PS had a “transient effect” of cementing agents (Yagüe *et al*. 2012b) which could be insufficient to maintain stability at the moment (9 months after incorporation) when a strong disruption over dry aggregates was applied (WSA procedure).

Different and positive linear relationships between WAS and SOC, SOC light fraction and SOC light fraction from 0.05 to 0.2 mm size were found (Figs. 5-2a, 5-2b and 5-2c). In fact, total SOC is important for soil aggregation although it includes more specific active fractions which are those most directly involved in aggregation (Huang *et al*., 2010). The light fraction of SOC has an important role in the formation and stability of soil structure, especially in the stabilization of soil macroaggregates (Kay, 1998; Yagüe *et al*., 2012b).

Changes in main chemical parameters

Dairy cattle manure, applied annually, increased soil salinity (with respect to the control) and P and K soil content (with respect to the control and MF), but there were no significant differences between treatments which included DCM (Table 5-6).

The phosphorus increase in DCM trials was 33.3 and 44.0 mg P kg soil^{-1} (equivalent to an annual accumulation of 2.8-3.7 mg P kg soil^{-1}). The potassium increase was 130.0 and 187.9 mg K kg soil^{-1} (equivalent to an annual accumulation of 10.8-15.7 mg K kg soil^{-1}). In the DCM plots, the maximum increment in average yields with respect to control (5.5 t ha^{-1}) was 2.1 t ha^{-1}. Thus, nutrient supply from soil was important and it can justify, in DCM plots, the increments in P and K soil content.

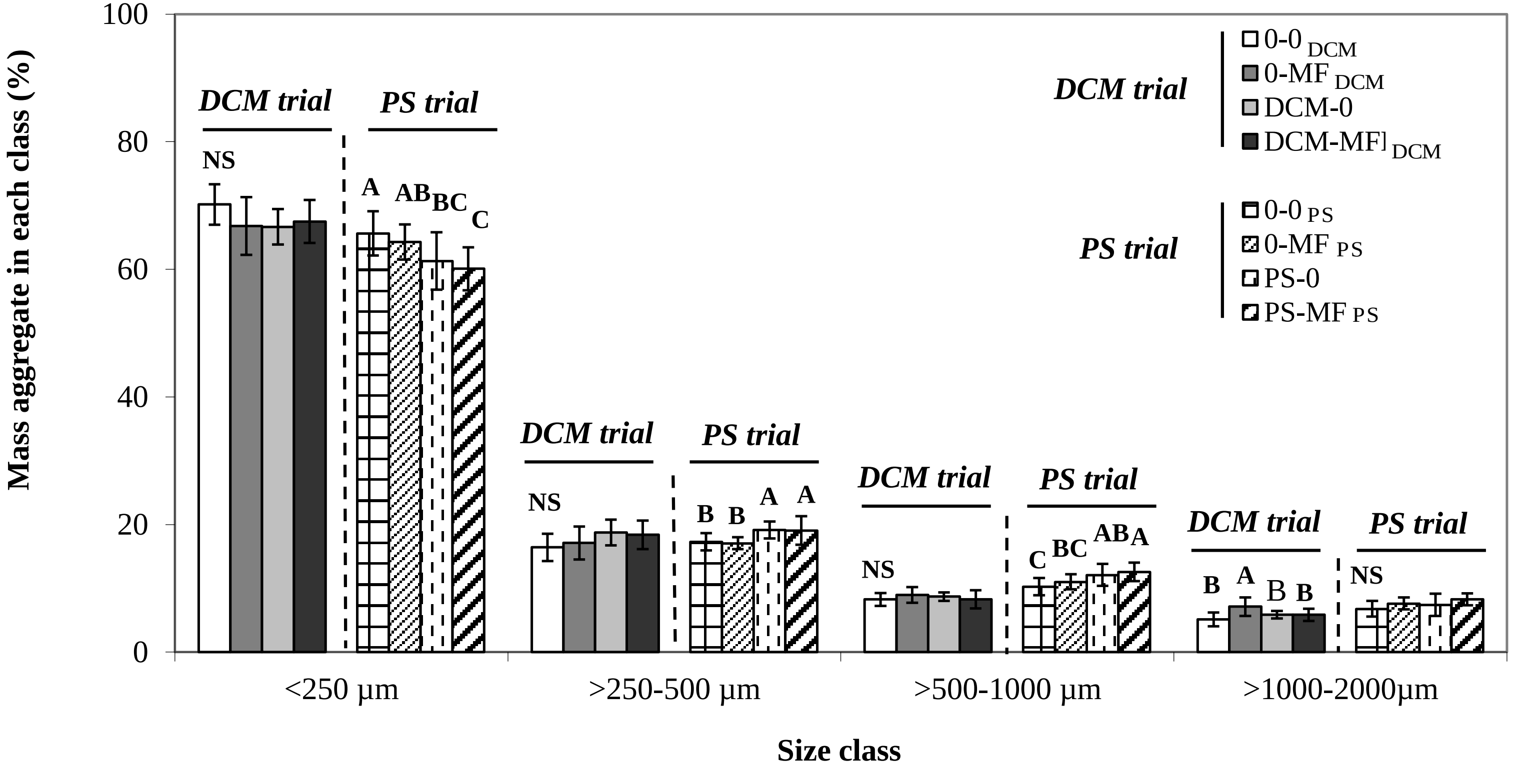

Figure 5-1. Mass of aggregates for each of the four size classes remaining after the implosion caused by the penetration of water into soil aggregates (slaking) in dairy cattle manure (DCM) and pig slurry (PS). Treatments include minerals (a) MF_{DCM} and MF_{PS}: mineral N fertilizer, applied at a rate of 40 or 50 kg N ha^{-1} yr^{-1}, respectively, as calcium ammonium nitrate (27 % N) at sidedressing; and organics (b) DCM and PS: dairy cattle manure and pig slurry applied just before sowing at an average rate of 22.5 or 47.3 t ha^{-1}, respectively. Mean values in each size class and for each trial followed by a different capital letter are significantly different at the α=0.05 probability level based on the Duncan Multiple Range Test. NS: no significant (p>0.05). Bars represent the standard error of three replicates.

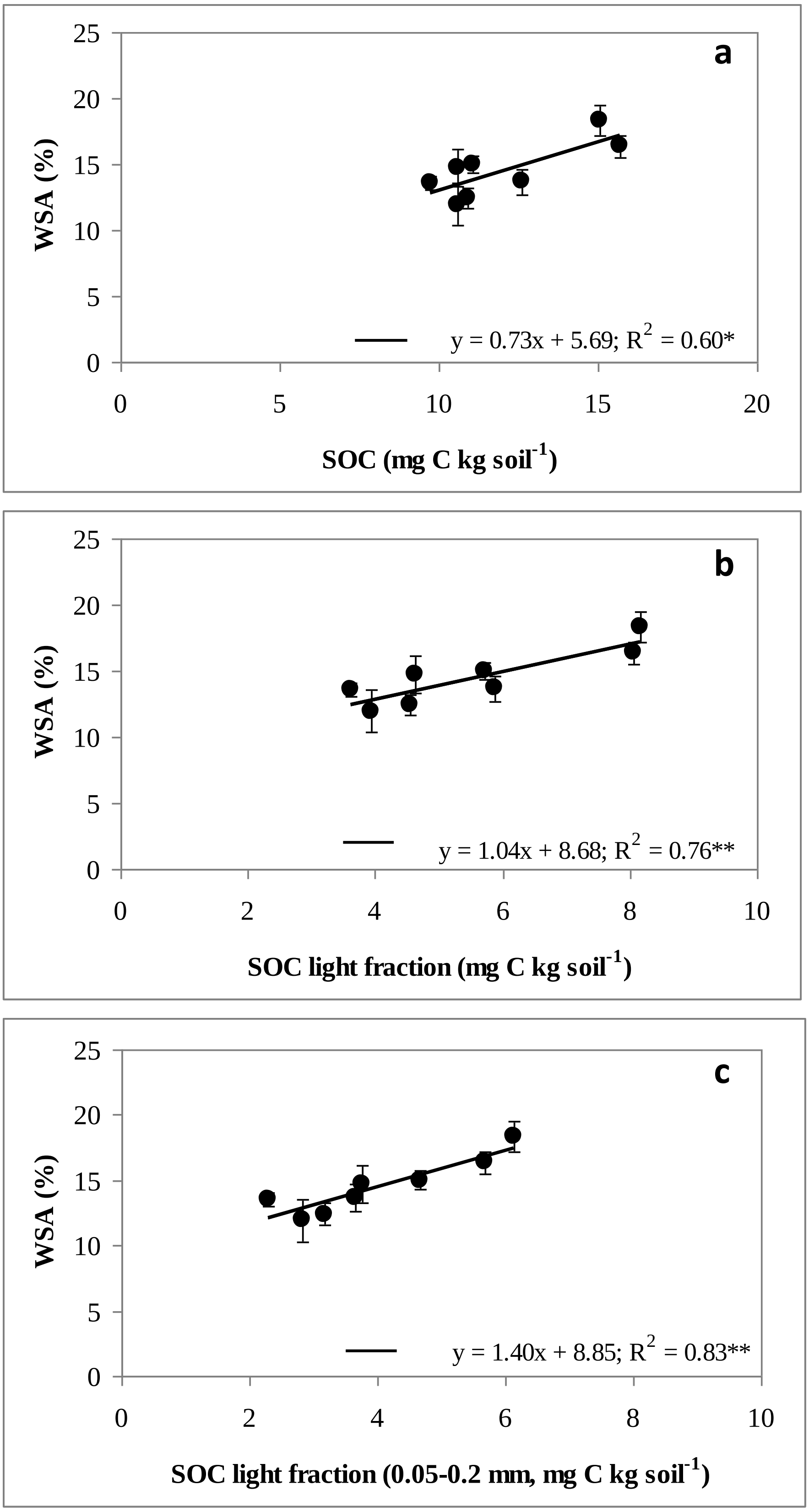

Figure 5-2. Relationship between (a) soil organic carbon (SOC), (b) SOC light fraction (0.05-2 mm); (c) SOC light fraction (0.05-0.2 mm) and water stable aggregates (WSA; % w/w). Data from the dairy cattle manure and the pig slurry plots were included. Bars represent the standard error of four replicates. Significance: * $p<0.05$; ** $p<0.01$.

This fact should alert us to the dangers of giving too much weight solely to N criteria in fertilization practices, and it implies that a more accurate fertilization management system must be found in order to avoid problems associated with an excess of macronutrients (P, K) in the near future. The introduction of leguminous crops or high P and K demanding crops could be an interesting means to reduce P and K excesses.

Pig slurry applied just at sowing also increased P and K soil content. However, when combined with mineral fertilizer it only increased K soil content (Table 5-6) with respect to the control and the MF treatment. In PS plots, the P content increased from 14.9 to 30.2g P kg soil^{-1} (equivalent to an annual accumulation of 1.2-2.5 mg P kg soil^{-1}). The K increase was from 77.9 to 152.0 mg K kg soil^{-1} (equivalent to an annual accumulation of 6.5-12.7 mg K kg soil^{-1}).

In PS trials, the addition of P by PS (100 kg P ha^{-1} yr^{-1}) was higher than that applied in DCM (53 kg P ha^{-1} yr^{-1}). However, the final average figures of P soil content (Table 5-6) did not reflect this difference. These results could be explained by an enhancement of P absortion by plants. Furthermore, when PS was complemented with MF, P soil content tended to decrease in PS trials, probably because the ammonium N fraction of MF favoured, even more, plant P absorption.

Phosphorus availability is a constraint in soils with a pH between 8.1 and 8.3, as it is easily fixed in calcium compounds. Besides, it is well known that the addition of ammonium-N in a fertilization formula enhances P absorption (Brewster *et al.*, 1991) because it produces H^+ in the soil solution-rhizosphere. These ions may temporarily bind the negative charged lime, organic matter and clay in soil (buffering ability). If the H^+ ions are not neutralized or bound to a soil particle, they create an acid environment close to roots (Hinsinger, 2001). The pH decreases and P uptake by the crop is enhanced. Pig slurry addition, with an important ammonium-N content (Yagüe *et al.*, 2012a) could positively affect wheat uptake of P and, consequently, it can slow down P accumulation in soil. Furthermore, organic materials with high P and low C/P ratios release more P (Gadgon and Simard, 1999), which can facilitate its availability.

With respect to the K addition, this was lower in slurry additions (83 kg K ha^{-1} yr^{-1}) than in manure ones (205 kg K ha^{-1} yr^{-1}).

After 12 years, in control ($0\text{-}0_{DCM}$; $0\text{-}0_{PS}$) and mineral fertilizer ($0\text{-}MF_{DCM}$; $0\text{-}MF_{PS}$) treatments, the addition of 34.5 kg P ha^{-1} yr^{-1} and 120.8 kg K ha^{-1} yr^{-1} did not affect the amounts of P and K in soil. This means that the P and K soil equilibrium was maintained. By contrast, the addition of DCM and PS increased the availability of these nutrients (Table 5-6).

Table 5-6. Average[†] of main soil chemical parameters measured after 12-yr of similar fertilization practices. Soil samples came from trials where dairy cattle manure (DCM) or pig slurry (PS) were applied.

Trial	**Treatment**	**$pH_{1:2.5}$**	**$EC_{1:5,\ 25ºC}$ (dS/m)**	**N (%)**	**P (Olsen)**	**ΔP**	**K (NH_4OAc, 1N, pH=7)**	**ΔK**
					------------------------ mg kg $soil^{-1}$			**----------------------**
DCM	**0-0 $_{DCM}$**	8.3	0.11B	0.15	37.7B	-	328.7B	-
	0-MF_{DCM}	8.2	0.11B	0.15	32.3B	-	310.8B	-
	DCM-0	8.2	0.13AB	0.22	71.0A	+33.3	458.9A	+130.0
	DCM-MF_{DCM}	8.2	0.14A	0.23	81.7A	+44.0	516.6A	+187.9
	Significance	NS	*	NS	***	-	***	-
PS	**0-0_{PS}**	8.2	0.11	0.14	35.8 B	-	291.8B	-
	0-MF_{PS}	8.2	0.12	0.19	35.0 B	-	259.4B	-
	PS-0	8.1	0.12	0.19	66.0 A	+30.2	443.2A	+152.0
	PS-MF_{PS}	8.1	0.12	0.18	50.7AB	+14.9	369.7A	+77.9
	Significance	NS	NS	NS	*	-	***	-

Δ: increment in the P or K soil content (plot value under organic fertilization – plot control value).

*significant at the 0.05 probability level; *** significant at the 0.001 probability level; NS: not significant (p>0.05).

[†] Within columns, means having a common letter are not significantly different according to DMRT (α=0.05).

[‡] MF_{DCM} and MF_{PS}: mineral N fertilizer, applied at a rate of 40 or 50 kg N ha^{-1} yr^{-1}, respectively, as calcium ammonium nitrate (27 % N) at sidedressing; DCM and PS: dairy cattle manure and pig slurry applied just before sowing at an average rate of 22.5 or 47.3 t ha^{-1}, respectively.

CONCLUSIONS

Long-term (12-yr) application of DCM (average rate of 23 t ha^{-1} yr^{-1}) gave a significant increase in soil organic carbon (4.5 g C kg^{-1}), mainly in the light fraction. Aggregates which were water stable against slaking disrupting forces, increased with the addition of DCM (up to 16.4-18.3 %) when compared with control or mineral fertilizer plots (14.7-15.0 %). The effect of PS with respect to the previous parameters was not significant, probably because the effects of PS are more transient than those of DCM. The MDW test was insufficiently accurate to allow detection of differences between fertilization treatments.

The light fraction of organic matter (0.05-0.2 mm size) was positively and linearly related with WSA (R^2=0.83; $p<0.01$). This fact indicates that changes in water stability of aggregates and organic matter fractions (i.e. light fraction, particularly 0.05 to 0.2 mm) may serve as indicators of soil quality related to agricultural fertilization practices.

Porosity in the 65-400 µm size range was increased with the use of pig slurry, thus PS application will probably increase water flow.

The build-up of phosphorus and potassium in soil, when PS and DCM are applied following the N demand criteria, clearly deserves further attention and should be considered in fertilization management strategies. Recommendations need to include widening crop rotations (e.g. by the introduction of leguminous crops) or other fertilization managements within a rotation (e.g. biennial application of manures which can alternate with fertilization using N only, applied as mineral N at sidedressing, if required). Further research is needed to improve nutrient management in a rotation concept from the agronomic and environmental aspects when using animal residues.

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6.- DISCUSSIÓ GENERAL

DISCUSSIÓ

Producció dels cultius

La utilització de dejeccions ramaderes en la fertilització dels cultius extensius augmenta, en general, els rendiments assolits i la qualitat de la producció. Però és necessari, quan s'apliquen dosis agronòmiques, complementar les aportacions de dejeccions ramaderes amb l'aplicació de fertilitzants nitrogenats minerals per tal d'assolir produccions màximes. De tota manera, la variabilitat interanual i entre cultius és elevada, tal i com ja han mostrat altres autors (Berenguer *et al*., 2008; Hernández *et al*., 2013; Bosch-Serra *et al*., 2015) en condicions similars a les d'aquest treball.

Producció de blat de moro

A curt termini, tres anys, les aportacions de dosis altes de fems de boví, sense complementar-les amb N mineral, no permeten obtenir les màximes produccions per un cultiu de blat de moro. Altres autors (Berenguer *et al*., 2008; Motavalli *et al*., 1993; Domingo *et al*., 2006) en assaigs amb durades de 3-4 anys, inferiors a les que es mostren en aquest treball, obtenen resultats similars. Altres autors (Daudén *et al*., 2004), treballant amb purins de porc, suggereixen un efecte de captura de N del sòl per degradar el C aportat per les dejeccions, que en el cas dels fems de boví seria més acusat pel major contingut en matèria orgànica.

Per un termini més llarg, els efectes acumulatius de les aplicacions de dejeccions en anys anteriors, permeten assolir les produccions màximes amb aportacions únicament de fems a dosis altes (60 Mg ha^{-1}). En aquests casos les aplicacions de N en cobertora no comporten en cap cas un increment del rendiment i, per contra, la major part dels anys se'n provoca una disminució (Apartat 2, Figura 2-2). Aquestes dosis de fems, però, no estan permeses per la legislació actual.

Per assolir màximes produccions, en sistemes d'elevada producció (13-15 Mg ha^{-1}) de blat de moro com el d'aquest treball, utilitzant nivells d'aplicació de fems propers a les dosis permeses actualment, és necessari aportar N mineral en cobertora a la dosi de 200 kg N ha^{-1}. Les aportacions anuals totals de N en aquest cas, al voltant dels 450 kg N ha^{-1}, són superiors a les permeses actualment per la legislació a Catalunya (Diari Oficial de la Generalitat de Catalunya, 2009). Aquesta legislació estableix límits màxims, segons la zona i condicions de reg, de N total que es pot aportar als cultius. Seria convenient revisar aquesta legislació de manera que la limitació considerés el nivell de producció que es pot assolir en cada parcel·la i permetés adaptar les aplicacions totals a les necessitats reals del cultiu. Potenciar la realització de balanços de N, que considerin les diferents fonts de N pel cultiu i les seves necessitats, permetria un raonament agronòmicament més adequat de la fertilització dels cultius.

La producció de blat de moro aportant només fertilitzants minerals no permet assolir les produccions màximes que s'obtenen quan s'aporten fems de boví. Utilitzant únicament adobs minerals s'arriba a la màxima producció amb aplicacions d'uns 200 kg N ha^{-1}, de forma similar al mostrat en altres treballs (Berenguer *et al*., 2009). Amb les dejeccions ramaderes s'aporten al sòl altres nutrients, a part de N, P i K, que contribueixen a una adequada nutrició del cultiu més difícil d'assolir només amb adob mineral.

L'increment de les aportacions de N en cobertora augmenta el contingut en N del gra de blat de moro tots els anys. A partir del segon any, també es produeix un increment d'aquest contingut en augmentar les dosis de fems de boví aplicades (Figura 2-3). En els darrers quatre anys de l'assaig, per la dosi més alta d'aplicació de fems de boví (60 Mg ha^{-1}) els aports creixents de N en cobertora no comporten un increment del contingut en N del gra.

Producció dels cereals d'hivern

Els cereals d'hivern són els cultius extensius més abundants en sistemes agrícoles de secà. En aquests, la nutrició no acostuma a ser el factor més limitant en la producció; sol ser-ho la disponibilitat d'aigua, molt variable entre anys en clima mediterrani.

En la zona d'estudi, amb clima mediterrani sub-humid, la producció de blat i ordi ha assolit nivells similars malgrat la menor precipitació mitjana en els anys de cultiu d'ordi, en concordança amb Cossani *et al*. (2007) que no va trobar evidències d'una diferent adaptació del blat i l'ordi a condicions de baixa disponibilitat d'aigua. De tota forma, per paràmetres de qualitat del gra, com la densitat i el pes del gra, s'assoleixen, la major part dels anys, nivells correctes en blat però no en ordi.

L'aplicació de purí de porcí a dosis agronòmiques en cereals d'hivern de secà comporta produccions màximes, a nivell anual, sense necessitat d'aportar N mineral en cobertora (Apartat 3, Figures 3-2 i 3-3). Però, de forma acumulada per un període de dotze anys, quan l'aplicació de purí es complementa amb N mineral en cobertora el rendiment del cultiu assolit és superior (Apartat 3, Taula 3-4) i també ho és el contingut en proteïna del gra, que és un paràmetre important de qualitat. Per contra, aquesta aportació de N mineral en cobertora tendeix a disminuir la densitat i el pes del gra, tant en blat com en ordi, fet que comercialment pot tenir importància en la valoració econòmica d'aquest producte.

Aspectes diversos de la dinàmica del N en el sòl

La producció del tractament testimoni s'estabilitza al voltant de 5 Mg ha^{-1}, a partir del tercer any, en blat de moro (Figura 2-2) i en 3 i 3,5 Mg ha^{-1}, a partir del setè any, en blat i ordi, respectivament (Figures 3-2 i 3-3). Són resultats similars als obtinguts per Hernández *et al*. (2013) en ordi, indicant també una estabilització de la mineralització del N orgànic del sòl. En l'assaig en blat de moro, els tractaments que reben fems de boví assoleixen produccions elevades amb uns nivells menors de N mineral al sòl a l'inici del cultiu (Figura 2-4), indicant que la mineralització del N dels fems, després de la seva aportació, augmenta la disponibilitat de N pel cultiu durant el seu creixement.

En els tractaments fertilitzats de l'assaig amb blat de moro el N mineral del sòl augmenta al final del cicle del cultiu. Com en altres treballs (Berenguer *et al*., 2008), aquest increment augmenta amb la dosi de N aplicada. El N mineral present en el sòl al final del cicle del cultiu pot rentar-se durant el periode de sòl nu (Nevens and Reheul, 2005; Zebarth *et al*., 1996) i contribuir a contaminar masses d'aigua freàtica. En el treball presentat s'han observant pèrdues de N en gairebé tots els tractaments i anys, incrementant-se en augmentar les dosis de N aplicades. De tota forma i per la metodologia de càlcul utilitzada, no totes les pèrdues es poden assignar al rentat de N mineral del sòl. Però sí que s'han mesurat rentats de nitrats importants en condicions similars (Domingo Olivé *et al.*, 2003)

En cereals d'hivern, els valors d'EAN (eficiència agronòmica del nitrogen) que s'obtenen són superiors als mesurats per altres autors (Bosch-Serra *et al.*, 2015) en condicions de secà més limitants i per un periode més curt d'assaig. Les eficiències més altes s'obtenen (Taula 3-5) quan només s'aplica fertilitzant mineral en cobertora, amb dosis d'aplicació de N molt diferents (Taula 3-3) de les aplicades amb els purins. Quan s'apliquen purins en condicions de secà i productivitat limitada, les dosis de N aportades no estan optimitzades i per tant disminueixen les eficiències en la utilització d'aquest nutrient. Per millorar les eficiències és necessari adequar les dosis de purins aplicades a les necessitats reals dels cultius, en aquestes condicions; i no agafar com a referència d'aplicació les dosis de N màximes permeses en la legislació actual.

Carboni organic i contingut de P i K en el sòl

En treballs realitzats amb dejeccions ramaderes, l'efecte en la producció dels cultius de les aplicacions de dejeccions ramaderes i la seva eficiència, en front de les aplicacions de N mineral, és el principal aspecte que es considera. Però les dejeccions ramaderes contenen, a part de nutrients, nivells diferents, segons el tipus de dejecció, de C orgànic: superior en les dejeccions sòlides –fems- que en les líquides –purins-. Quan s'apliquen al sòl poden contribuir a incrementar el nivell de C orgànic del sòl (Haynes i Naidu, 1998; Quilty i Cattle, 2011; Diacono i Montemurro, 2010). En aquest treball es mostra que l'aportació anual de dosis creixents de fems de boví i purins de porcí han contribuït a incrementar progressivament el contingut de C orgànic del sòl (Apartat 4, Taula 4-IV; Apartat 5, Taula 5-4). En un termini d'onze i dotze anys s'han observat increments anuals del contingut en C del sòl de 0,35-0,40 g C kg^{-1}, per aportacions de fems dins els límits de dosis permeses per la legislació, i de 0,21 g C kg^{-1}, en el cas d'aplicacions de purins, respecte un maneig utilitzant únicament fertilitzants minerals. Alguns autors (Jaiarree *et al.*, 2014) recomanen d'aplicar les dejeccions prioritàriament en sòls amb baixos continguts de C orgànic i contribuir d'aquesta forma al segrest de C atmosfèric en el sòl.

El C orgànic del sòl és important principalment pel paper que juga afavorint altres aspectes de qualitat del sòl, tals com l'estabilitat dels agregats (Tisdall i Oades, 1982), que en augmentar protegeix en front de l'erosió, i l'activitat de la fauna, que pot afavorir l'infiltració de l'aigua en el sòl a partir de l'augment de la porositat (Lee i Foster, 1991). Aquest treball aporta informació en aquests aspectes en un sistema agrícola mediterrani.

S'ha observat que les aplicacions anuals de dejeccions ramaderes, tant fems com purins, incrementen a llarg termini el contingut del sòl en P i K disponible pel cultiu (Apartat 5, Taula 5-6) fins a nivells considerats molt alts o, fins i tot, excessius en sistemes cerealícoles de secà. És necessari parar atenció a aquest fet i reconsiderar el maneig d'aquests sistemes: planificant les aplicacions d'aquests productes utilitzant criteris diferents al del N, o introduint a les rotacions altres cultius amb majors necessitats en aquests nutrients.

Estabilitat dels agregats del sòl

A llarg termini, l'aplicació anual de fems de boví ha augmentat l'estabilitat dels agregats de l'horitzó superficial del sòl, tant en un sistema de monocultiu de blat de moro en regadiu (Apartat 4, Taula 4-III) –amb increments del 37 % d'agregats estables a la disrupció per aigua (WSA) i del 29 % en el diàmetre mig ponderat (MWD) dels agregats- com en un sistema de cereals d'hivern en secà (Apartat 5, Taula 5-5) –amb increments del 17 % de WSA, però sense diferències en el MWD- tal com apuntaven altres autors en treballs realitzats en altres ambients (Aoyama et al., 1999). Les aplicacions de dosis altes de fems no han incrementat aquests resultats positius respecte les aplicacions de dosis agronòmiques. Els resultats obtinguts amb l'aplicació de purins són menys concloents, tot i observar una tendència a una major estabilitat quan s'apliquen purins de porcí, probablement perquè els efectes d'aquests materials són més transitoris (Yagüe *et al.*, 2012) que els de les dejeccions sòlides com els fems.

El fet que aquests increments es produeixin, en ambdós casos, en un sòl amb un contingut baix en argila -un dels components del sòl que contribueix a la formació i estabilitat dels agregats- és especialment rellevant pel maneig i la protecció enfront de la degradació d'aquests sòls.

En els dos sistemes agraris estudiats i pels dos tipus de dejeccions utilitzades (fems de boví i purins de porcí d'engreix) l'estabilitat dels agregats del sòl es relaciona directament de forma clara (Apartat 4, Figura 4-2; i Apartat 5, Figura 5-2) amb el contingut en C orgànic en la fracció lleugera de la matèria orgànica del sòl. Aquesta fracció és la que és més sensible a canvis en el maneig del sòl (Bremer *et al.*, 1994) i correspon a la matèria orgànica en descomposició, provinent de les plantes i les dejeccions, que estimula la producció de polisacàrids, per part de la microflora del sòl, que contribueixen a augmentar l'estabilitat dels agregats (Tisdall i Oades, 1982). Representa un indicador inicial per preveure els canvis a llarg termini en la qualitat del sòl induïts per canvis en les tècniques de maneig d'aquest (Leifeld i Kögel-Knabner, 2005).

Altres paràmetres de qualitat del sòl

L'aplicació de dejeccions ramaderes també afecta altres paràmetres importants de qualitat del sòl.

D'una banda la porositat, en què s'observa l'increment del percentage de porus de mida més gran (> 400 µm) amb aplicacions de fems de boví a dosis agronòmiques en blat de moro de regadiu respecte el testimoni (Figura 4-4), i el dels porus de mida mitjana (entre 65 i 400 µm) amb aplicacions de purins de porcí en cereals de secà (Taula 5-3). La importància de tenir sòls amb un espai més gran ocupat per porus és perquè aquests afavoreixen l'aireació del sòl i la infiltració de l'aigua de reg o pluja, reduint l'escolament potencial d'aigua amb poder erosiu (Dosskey *et al.*, 2007).

D'altra banda, també s'ha vist que l'abundància de cucs de terra augmenta a mesura que augmenta la dosi de fems de boví aplicada (Apartat 4, Figura 4-3), tot i que només s'observen diferències estadísticament significatives entre la dosi més alta de fems aplicats (60 Mg ha^{-1}) i el tractament amb fertilització mineral. Altres autors (Biau *et al.*, 2012) obtenen resultats similars en aplicacions de purins de porcí en sistemes de monocultiu de blat de moro d’elevada productivitat en regadiu en zones semiàrides. Aquests i altres autors (Lee i Foster, 1991) destaquen que aquest paràmetre pot ser un indicador de la qualitat del sòl relativament fàcil de mesurar.

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7.- CONCLUSIONS GENERALS

CONCLUSIONS GENERALS

Les conclusions principals d'aquesta tesi són:

1.- Per obtenir produccions elevades (al voltant de 15 Mg ha^{-1}) de blat de moro en regadiu cal combinar aplicacions de fems de boví de llet en fons (30 Mg ha^{-1}) amb aportacions de N mineral (150-200 kg N ha^{-1}) en cobertora.

Aplicar anualment només fems de boví a dosis superiors a les permeses (60 Mg ha^{-1}) i sense aportar N en cobertora pot permetre assolir produccions similars, però amb dosis de N superiors a les permeses actualment per la legislació, i amb pèrdues de N cap al medi superiors. Aplicacions de N més elevades no comporten una major producció de blat de moro i augmenten les possibles pèrdues de N.

2.- El contingut en N del gra de blat de moro augmenta quan s'incrementa l'aportació de fertilitzant nitrogenat mineral en cobertora i, excepte els primers anys, per dosis creixents de fems de boví de llet.

3.- Les produccions de blat i ordi en secà, en el conjunt de dotze anys, són superiors a mesura que s'augmenta la quantitat de N aplicada a aquest cultius. També s'incrementa de forma marcada el contingut en proteïna del gra de cereal.

Aportar purins abans de la sembra contribueix a augmentar les produccions de cereal d'hivern i el contingut en proteïna del gra. Complementar aquestes aportacions de fons amb adob mineral en cobertora també augmenta la producció de gra i el contingut en proteïna d'aquest. Per contra, l'aplicació d'adob nitrogenat mineral en cobertora tendeix a disminuir tant la densitat com el pes del gra de blat i ordi.

4.- L'eficiència en la utilització del N és marcadament menor quan s'apliquen purins en fons que en el cas d'aplicacions només de N mineral en cobertora. Probablement per les aportacions excessives de N amb els purins en un ambient de secà, de productivitat limitada lligada a les precipitacions i sòl percolant, aplicant les dosis màximes permeses per la legislació.

Ajustar a les necessitats dels cultius les dosis de N aportades amb aquests fertilitzants orgànics pot contribuir a apropar les eficiències obtingudes a les dels fertilitzants nitrogenats minerals.

5.- Quan es fertilitzen, durant períodes llargs de més de deu anys, els cultius amb fems i purins considerant essencialment el criteri N i la legislació que regula el seu aport es contribueix a l'augment del contingut de P i K disponible en el sòl.

6.- Les aplicacions de fems de boví augmenten la quantitat de C orgànic en el sòl respecte la fertilització amb adobs minerals, especialment en la fracció lleugera de la matèria orgànica del sòl, tant en secà com en regadiu. Pel cas dels purins, no s'observen increments significatius, probablement a causa del menor contingut en C orgànic dels purins.

7.- Les aplicacions anuals de fems de boví augmenten l'estabilitat dels agregats del sòl en front dels processos d'humectació ràpida del sòl ("slaking"), tant en condicions de reg com en condicions de secà, millorant la resiliència del sòl respecte processos de desestabilització per part de la pluja o el reg.

8.- Existeix una relació linear positiva molt significativa entre la quantitat de C orgànic en la fracció lleugera de la matèria orgànica del sòl i l'estabilitat dels agregats a l'humectació ràpida del sòl, pel cas dels fems de boví. El contingut en C orgànic de la fracció lleugera de matèria orgànica entre 0,05 i 0,2 mm pot ser un bon indicador de la qualitat del sòl en relació a l'efecte de les pràctiques de fertilització.

9.- L'aplicació continuada de fems de boví de llet i/o purins de porcí a dosis agronòmiques ha provocat un augment de la presència de porus de mida mitjana-gran (>65 µm), que pot comportar un increment de la infiltració de l'aigua de pluja o reg, evitant escolament, i de la permeabilitat del sòl.

10.- L'abundància de cucs de terra en l'horitzó superficial del sòl és superior quan s'apliquen dosis altes de fems de boví de forma repetida. No s'ha trobat cap relació amb els canvis observats en l'abundància i forma dels porus del sòl.