Universitat de Lleida

Ús sostenible de fertilitzants orgànics en sistemes agrícoles mediterranis

Carlos A. Ortiz Gama

http://hdl.handle.net/10803/688937

ADVERTIMENT. L'accés als continguts d'aquesta tesi doctoral i la seva utilització ha de respectar els drets de la persona autora. Pot ser utilitzada per a consulta o estudi personal, així com en activitats o materials d'investigació i docència en els termes establerts a l'art. 32 del Text Refós de la Llei de Propietat Intel·lectual (RDL 1/1996). Per altres utilitzacions es requereix l'autorització prèvia i expressa de la persona autora. En qualsevol cas, en la utilització dels seus continguts caldrà indicar de forma clara el nom i cognoms de la persona autora i el títol de la tesi doctoral. No s'autoritza la seva reproducció o altres formes d'explotació efectuades amb finalitats de lucre ni la seva comunicació pública des d'un lloc aliè al servei TDX. Tampoc s'autoritza la presentació del seu contingut en una finestra o marc aliè a TDX (framing). Aquesta reserva de drets afecta tant als continguts de la tesi com als seus resums i índexs.

ADVERTENCIA. El acceso a los contenidos de esta tesis doctoral y su utilización debe respetar los derechos de la persona autora. Puede ser utilizada para consulta o estudio personal, así como en actividades o materiales de investigación y docencia en los términos establecidos en el art. 32 del Texto Refundido de la Ley de Propiedad Intelectual (RDL 1/1996). Para otros usos se requiere la autorización previa y expresa de la persona autora. En cualquier caso, en la utilización de sus contenidos se deberá indicar de forma clara el nombre y apellidos de la persona autora y el título de la tesis doctoral. No se autoriza su reproducción u otras formas de explotación efectuadas con fines lucrativos ni su comunicación pública desde un sitio ajeno al servicio TDR. Tampoco se autoriza la presentación de su contenido en una ventana o marco ajeno a TDR (framing). Esta reserva de derechos afecta tanto al contenido de la tesis como a sus resúmenes e índices.

WARNING. Access to the contents of this doctoral thesis and its use must respect the rights of the author. It can be used for reference or private study, as well as research and learning activities or materials in the terms established by the 32nd article of the Spanish Consolidated Copyright Act (RDL 1/1996). Express and previous authorization of the author is required for any other uses. In any case, when using its content, full name of the author and title of the thesis must be clearly indicated. Reproduction or other forms of for profit use or public communication from outside TDX service is not allowed. Presentation of its content in a window or frame external to TDX (framing) is not authorized either. These rights affect both the content of the thesis and its abstracts and indexes.

Universitat de Lleida

TESI DOCTORAL

Ús sostenible de fertilitzants orgànics en sistemes agrícoles mediterranis

Carlos A. Ortiz Gama

Memòria presentada per optar al grau de Doctor per la Universitat de Lleida
Programa de Doctorat en Ciència i Tecnologia Agrària i Alimentària

Directora
Dra. Àngela D. Bosch Serra
Dra. Maria Gabriela de los Ángeles Molina

Tutora
Dra. Àngela D. Bosch Serra

JUNY 2023

Universitat de Lleida

TESI DOCTORAL

Ús sostenible de fertilitzants orgànics en sistemes agrícoles mediterranis

Memòria presentada per

Carlos A. Ortiz Gama

En satisfacció dels requisits necessaris per optar al grau de Doctor

Tutora i codirectora. Dra. Àngela D. Bosch Serra
Codirectora. Dra. Maria Gabriela de los Ángeles Molina

Lleida, juny de 2023

Agraïments

Crec rellevant destacar que aquest treball se sustenta gràcies a què, fa més de 20 anys, el Departament d’Agricultura, Ramaderia i Pesca, amb certes persones visionàries al capdavant, va prendre l’encertada decisió d’iniciar assajos de llarga durada amb fertilitzants orgànics, tan importants i que, actualment, comencen a tenir el reconeixement que es mereixen. Aquest recolzament va ser complementat per la Universitat de Lleida, qui va donar també suport i executar la majoria de tasques associades per al seu desenvolupament i difusió. No deixar de banda l’elevat cost anual que la recerca suposa, on el cofinançament rebut mitjançant projectes estatals (INIA: REN01-1590, RTA04-114, RTA2010-126, RTA2013-57-C5-5 i RTA2017-88-C3-3) o europeus (LIFE12 ENV/ES/647) és totalment necessari. Finalment, agrair a totes les persones propietàries de les parcel·les comercials haver permès fer recerca a “casa seua” al llarg de tot aquest temps.

Resum

En un context d’economia circular, cal vetllar per maximitzar l’aprofitament dels nutrients i augmentar, com a conseqüència, l’eficiència dels sistemes agrícoles mediterranis, en línia amb les pautes que marca l’estratègia comunitària de la Granja a la Taula en matèria de fertilització.

Ara bé, el maneig de la fertilització en aquests sistemes és molt complex, on part de la dificultat de gestió es deu a la dependència en la disponibilitat d’aigua pels cultius. Sota aquest context, cal sumar-hi l’elevada disponibilitat de dejeccions ramaderes i d’altres esmenes orgàniques, així com un ús encara molt elevat d’adobs minerals. L’objectiu general de la tesi consisteix en aprofundir en la millora de la gestió de la fertilització orgànica en cultius extensius, prenent com a base el nitrogen, i atenent a les especificitats existents en diferents sistemes agrícoles mediterranis. Els treballs s’han executat en tres escenaris diferents, en cultius extensius i sòls calcaris: i) un camp experimental en secà semiàrid durant el període 2003-2016; ii) un camp experimental en secà subhumit durant els períodes 2000-2010 i 2013-2020; iii) una àrea de regadiu d’unes 700 ha durant el període 2014-2018.

Els secans semiàrids estudiats (~400 mm) presenten una gran variabilitat de producció que en els anys secs se situa entorn dels 2500, 2000 i 1900 kg/ha en ordi, blat i colza, respectivament, mentre que els pocs anys més humits les produccions són properes als 4000 i 4600 kg/ha en ordi i blat, respectivament. En aquest escenari, cal efectuar un enfocament més holístic de la fertilització que inclogui objectius productius, que garanteixin els rendiments en anys plujosos, i mediambientals, que tinguin en compte la reposició de nutrients i la reducció del N residual al sòl.

En els secans subhumits (~450 mm), les produccions mitjanes s’incrementen fins a 1,4 cops respecte els secans semiàrids i també ho fan, tot i que en menor mesura (x1,1), les exportacions de N. Els valors més elevats (61 %) d’eficiència en l’ús del nitrogen (NUE, N exportat en collita/N aplicat) s’han obtingut amb la dosi més baixa de purins (171 kg N/ha). Els valors de NUE obtinguts avalen la recomanació de reduir les aportacions de N. L’efecte residual de l’aplicació de dosis puntuals de purins a 20 m^3/ha, com sumatori del N disponible 3 anys posteriors a l’aplicació, ha estat del 22 % sobre el N total aplicat. L’increment de l’eficiència del N també es pot aconseguir amb la implementació de crucíferes i lleguminoses en la rotació amb ordi. La baixa disponibilitat d’aigua compromet les produccions d’aquests cultius, de manera que es considera rellevant continuar compensant econòmicament la inclusió d’aquests cultius en aquestes zones.

Els regadius (600 mm) incrementen la disponibilitat d’aigua fins als ~1000 mm. Les extraccions de N tripliquen els valors de zones de secà, però la intensificació productiva va acompanyada d’acumulacions de nutrients, com el P assimilable, que superen els valors de no resposta recomanats per als cultius. S’observen també desequilibris en la fertilització de les parcel·les estudiades, tant per excés com per defecte. S’ha detectat una correlació significativa entre l’aportació d’esmenes orgàniques i els continguts d’oligoelements com el Cu, Zn i Mn (extracció amb DTPA) i Cu i Zn totals (extracció àcida), cosa que incrementa la disponibilitat de nutrients al sòl, però, alhora, és un avís, pels potencials efectes nocius a llarg termini si continuen acumulant-se. Per contra, la utilització d’adobs minerals alerta sobre una potencial acumulació de Cd. Finalment, l’aplicació continuada d’esmenes orgàniques dona lloc a zones crítiques, entre 60 i 80 mg/kg (P Olsen), on s’ha observat que el P es desplaça verticalment cap a capes més profundes.

Resumen

En un contexto de economía circular, es necesario velar por maximizar el aprovechamiento de los nutrientes y aumentar la eficiencia de los sistemas agrícolas mediterráneos, en línea con la estrategia comunitaria de la Granja a la Mesa en materia de fertilización.

Sin embargo, el manejo de la fertilización en estos sistemas es muy complejo, y parte de la dificultad de gestión se debe a la dependencia en la disponibilidad de agua para los cultivos. A este contexto, hay que sumarle la elevada disponibilidad de deyecciones ganaderas y otras enmiendas orgánicas, así como un uso todavía muy elevado de abonos minerales. El objetivo general de la tesis consiste en profundizar en la mejora de la gestión de la fertilización orgánica en cultivos extensivos, tomando como base el N, y atendiendo a las especificidades existentes en distintos sistemas agrícolas mediterráneos. Los trabajos se han llevado a cabo en cultivos extensivos y suelos calcáreos, en 3 escenarios diferentes: i) un campo experimental en secano semiárido durante el período 2003-2016; ii) un campo experimental en secano sub-húmedo durante los períodos 2000-2010 y 2013-2020; iii) un área de regadío de unas 700 ha durante el período 2014-2018.

Los secanos semiáridos (~400 mm) presentan una gran variabilidad de producción, que en los años secos se sitúa en los 2500, 2000 y 1900 kg/ha en cebada, trigo y colza, respectivamente, mientras que los pocos años húmedos las producciones son cercanas a los 4000 y 4600 kg/ha en cebada y trigo, respectivamente. En este escenario, debe efectuarse un enfoque más holístico de la fertilización que incluya objetivos productivos, que garanticen los rendimientos en años lluviosos, y medioambientales, que tengan en cuenta la reposición de nutrientes y la reducción del N residual en el suelo.

En los secanos sub-húmedos (~450 mm), las producciones medias se incrementan hasta 1,4 veces respecto a los secanos semiáridos y también lo hacen, aunque en menor medida (x1,1), las exportaciones de N. Los valores más elevados (61 %) de eficiencia en el uso del N (NUE, N exportado en cosecha/N aplicado) se han obtenido con la dosis más baja de purines (171 kg N/ha). Los valores de NUE obtenidos avalan la reducción de los aportes de N. El efecto residual de la aplicación de dosis puntuales de purines a 20 m^3/ha, como suma del N disponible 3 años tras la aplicación, ha sido del 22 % del N total aplicado. El incremento de la eficiencia del N también se puede conseguir introduciendo crucíferas y leguminosas en la rotación con cebada. La baja disponibilidad de agua compromete las producciones de estos cultivos, por lo que se considera relevante seguir compensando económicamente la inclusión de estos cultivos.

Los regadíos (600 mm) incrementan la disponibilidad de agua hasta los ~1000 mm. Las extracciones de N triplican los valores de secano, pero la intensificación productiva tiende a la acumulación de nutrientes, como P asimilable, que superan los valores de no respuesta recomendados para los cultivos. Se observan también desequilibrios en la fertilización de las parcelas, tanto por exceso como por defecto. Se ha detectado una correlación significativa entre el uso de enmiendas orgánicas y el contenido de oligoelementos como Cu, Zn y Mn (extracción DTPA), y Cu y Zn totales (extracción ácida), lo que incrementa la disponibilidad de nutrientes en el suelo, pero, al mismo tiempo, es un aviso, por los potenciales efectos nocivos a largo plazo si siguen acumulándose. Por el contrario, el uso de abonos minerales alerta sobre una acumulación potencial de Cd. Por último, la aplicación continuada de enmiendas orgánicas da lugar a zonas críticas, entre 60 y 80 mg/kg (P Olsen), donde se ha observado que el P se desplaza verticalmente hacia capas más profundas.

Abstract

In a context of circular economy, it is necessary to ensure that the use of nutrients is maximized and, as a consequence, to increase the efficiency of Mediterranean agricultural systems, in line with the guidelines established by the community strategy of the Farm on the Table in terms of fertilization.

However, the management of fertilization in these systems is very complex, where part of its difficulty is due to the crops water dependence on water availability. The high availability of livestock manure and other organic amendments in such areas, as well as the high use of mineral fertilizers, are also needed to be considered. The general objective of the thesis is to improve the management of organic fertilization in extensive crops, based on nitrogen, and taking into account the existing specificities in different Mediterranean agricultural systems. The works have been carried out in three different scenarios, in extensive crops and calcareous soils: i) an experimental field in a semi-arid rainfed area during the 2003-2016 period; ii) an experimental field in a sub-humid rainfed area during the periods 2000-2010 and 2013-2020; iii) an irrigated area of about 700 ha during the 2014-2018 period.

The semi-arid drylands (~400 mm) present a great variability of production that in the dry years is around 2,500, 2,000 and 1,900 kg/ha in barley, wheat and rapeseed, respectively, while in the few wetter years it can achieve averages of 4000 and 4600 kg/ha in barley and wheat, respectively. In this scenario, a more holistic approach to fertilization must be carried out that includes productive objectives, in order to guarantee yields in rainy years, and environmental ones, not deplete soil nutrients, and to minimize the accumulation of residual N.

In the sub-humid drylands (~450 mm), the average productions increase up to 1.4 times compared to the semi-arid drylands and so do, although to a lesser extent (x1.1), the N uptake. The highest values (61 %) of the N Use Efficiency (NUE, N exported in harvest/N applied) index have been obtained with the lowest dose of slurry (171 kg N/ha). The NUE values obtained support the recommendation to reduce N inputs. The residual effect of the application of punctual doses of pig slurry at 20 m^3/ha, as the sum of the N available 3 years after application, has been 22 % on the total N applied. A better N efficiency can also be achieved with the implementation of cruciferous and legumes in the rotation with barley. The low availability of water compromises the production of these crops, so it is considered relevant to continue economically compensating the inclusion of these crops in these areas.

Irrigation (600 mm) increases the availability of water up to ~1000 mm. N extractions triple the values of rainfed areas, but productive intensification drives to accumulation of nutrients, such as available P, which exceeds the non-response values recommended for crops. Imbalances are also observed in the fertilization fields, both due to excess and deficiency. A significant correlation has been detected between the contribution of organic amendments and the contents of oligoelements such as Cu, Zn and Mn (extraction with DTPA) and total Cu and Zn (acid extraction), which increases the availability of nutrients in the soil, but, at the same time, is a warning, for the potential long-term harmful effects if they continue to accumulate. On the contrary, the use of mineral fertilizers warns about a potential accumulation of Cd. Finally, the continuous application of organic amendments gives rise to critical zones, between 60 and 80 mg/kg (P Olsen), where it has been observed that the P moves vertically into deeper layers.

Índex general

Índex de figures

Índex de taules

Llistat d’abreviatures

AIC: criteri d'informació d'Akaike; criterio de información de Akaike; Akaike information criterion

AvCu: coure disponible; cobre disponible; available copper

AvK: potassi disponible; potasio disponible; available potassium

AvMn: manganès disponible; manganeso disponible; available manganese

AvP: fòsfor disponible; fósforo disponible; available phosphorus

AvZn: zinc disponible; zinc disponible; available zinc

CCE: carbonat càlcic equivalent; carbonato cálcico equivalente; calcium carbonate equivalent

EC: conductivitat elèctrica; conductividad eléctrica; electrical conductivity

Ev: valors eigen; valores eigen; eigenvalues

FNE: N fertiltizant equivalent; N fertilizante equivalente; fertilizer N equivalent

GAEC: Bones Pràctiques Agràries o Mediambientals; Buenas Prácticas Agrarias y Medioambientales; Good Agricultural and Environmental Conditions

GY: rendiment de gra; rendimiento de grano; grain yield

MN: fertilitzant mineral nitrogenat; fertilizante mineral nitrogenado; mineral N fertilizer

Napl: N aplicat; N aplicado; applied N

Nexp: N exportat; N exportado; uptaken N

Nfin: N al final de l'assaig; N al final del ensayo; N at the end of the trial

Nini: N a l'inici de l'assaig; N al inicio del ensayo; N at the beggining of the trial

Nsow: N en fons; N en fondo; N at sowing

Ntop: N a cobertora; N en cobertera; N at topdressing

NUE: eficiència en l'ús del N; eficiencia en el uso del N; N use efficiency

OC: carboni orgànic; carbono orgánico; organic carbon

PC: component principal; componente principal; principal component

PCA: anàlisi de components prinicipals; análisis de componentes principales; principal component analysis

PS: purí de porc; purín de cerdo; pig slurry

RE: efecte residual; efecto residual; residual effect

RE1: efecte residual de primer any; efecto residual de primer año; first year residual effect

RE2: efecte residual de segon any; efecto residual de segundo año; second year residual effect

RE3: efecte residual de tercer any; efecto residual de tercer año; third year residual effect

WPNU: N extret per tpota la planta; N extraído por toda la planta; whole plant N uptake

Capítol 1. Introducció i objectius generals

1.1 Introducció general

La fertilització dels sòls ha esdevingut un dels pilars fonamentals de l'alimentació de la humanitat des de l'antiguitat, amb cites sobre la importància de l'aplicació d'esmenes orgàniques per al profit dels cultius que apareixen en textos de l'Antiga Roma (Cato & Varro, 1934). Però no és fins a principis del segle XX que s'introdueix la fabricació massiva dels adobs minerals, gràcies al conegut procés Haber-Bosch que permetia la síntesi d'amoníac (NH_3) a partir del N de l'atmosfera (Erisman *et al*., 2008). L'aplicació d'aquests fertilitzants de síntesi, juntament amb altres factors com una maquinària cada cop més eficient o unes varietats de cultius més productives, van jugar un paper fonamental i sense precedents en la producció d'aliments a escala mundial, especialment a partir de la segona meitat del segle passat.

El sector agrícola no va ser l'únic que va experimentar canvis, sinó que la ramaderia també va rebre influències de l'evolució tecnològica, la millora genètica animal, i els increments de producció dels cultius que serien una font bàsica per a la fabricació de pinsos. D'aquesta manera, la ramaderia va intensificar-se en zones com el nord-est de l'Estat espanyol, amb especial rellevància a la part oriental de la Vall de l'Ebre. El cas més destacat seria el de Catalunya, que va especialitzar-se ja des dels anys 60 en l'engreix de porcí i de pollastres (MAPA, 1961; MAPA, 1993), bàsicament per una qüestió d'economia d'escala que mirava de reduir els costos de les explotacions i lligat també a la interacció entre la ramaderia i les fàbriques de pinsos que van donar lloc a les empreses integradores.

L'increment dels ingressos dels sectors agrícola i ramader, i l'alimentació de la població després de períodes de guerra (primera guerra mundial, guerra civil espanyola, i segona guerra mundial) van suposar uns anys de recuperació econòmica per al continent. Això va donar lloc a una segona meitat de segle XX de benestar en què, malauradament, la intensificació productiva també va contribuir a pertorbar els sistemes naturals, amb impactes sobre el medi ambient, el clima i la salut humana. Durant aquest període ja es començava a sentir parlar del concepte de sostenibilitat (NEPA, 1969) en el sentit de continuar produint, però sense malmetre l'entorn i pensant sobretot en les generacions futures.

La intensificació de la ramaderia a Catalunya ha continuat fins ben entrat el segle XXI i ha resultat una peça clau per a un sector agroalimentari que actualment és un dels principals pilars de l'economia catalana amb la generació de l'equivalent al 16 % del PIB l'any 2017 (PRODECA, 2019). En unes dècades, s'ha consolidat la creació d'una potent indústria càrnia, juntament amb el creixement sostingut de la indústria de pinsos, així com altres indústries auxiliars. Les explotacions ramaderes van iniciar un període de modernització que implicava més productivitat i eficiència. Després d'unes quantes dècades, Catalunya s'ha convertit no només en un gran productor, sinó que s'ha posicionat com un gran fabricant. El sector porcí català predomina sobre l'aviram i el boví, amb el 76, 11 i 12 % de les unitats de bestiar existents (INE, 2020), i ocupa la quarta posició a nivell europeu després d'altres regions, NUTS 2 com la Baixa Saxònia (Alemanya), l'Aragó (Espanya), o la Bretanya (França) (Eurostat, 2021).

Durant els darrers anys, aquest creixement ha començat a desaccelerar-se en part com a conseqüència de normatives comunitàries entrades en vigor dècades enrere, com ara la Directiva Nitrats (OJ, 1991), la Directiva Marc de l'Aigua (OJ, 2000), la Directiva IPPC (OJ, 2010), o la Directiva de Sostres (OJ, 2016), entre altres. En aquest context, als anys 90 la UE va posar el focus en els nitrats d'origen agrari amb una regulació comunitària per prevenir i revertir la contaminació de les aigües. Així, la Directiva Nitrats, encara vigent i sense modificacions rellevants en més de 30 anys de vida, transposada als estats membres (BOE, 2022), obliga a la designació i actualització de zones vulnerables a la contaminació per nitrats d'origen agrari, a elaborar programes d'acció d'obligat compliment per a aquestes zones designades (DOGC, 2019), a controlar-ne la seva eficàcia, a elaborar programes de controls per al seguiment de la qualitat de les aigües, a dissenyar un codi de bones pràctiques agràries de caràcter voluntari per als agricultors (DOGC, 1998a), així com a proporcionar formació i informació al sector, quan es consideri necessari. La primera designació de zones vulnerables a Catalunya es va fer l'any 1998 (DOGC, 1998b). Des de llavors, s'ha disposat de majors coneixements, la qual cosa ha propiciat revisions més exhaustives al llarg dels anys (DOGC, 2004, 2009, 2015 i 2021). L'any 2021, més d'un terç de la superfície de Catalunya és declarada com a vulnerable, tot afectant gairebé a la meitat dels municipis (DACC, 2022).

Tanmateix, la Comissió Europea presenta el Pacte Verd Europeu (COM, 2019) com a camí a seguir per a un creixement sostenible en matèria de Clima i Medi Ambient, amb l'Estratègia de la Granja a la Taula (COM, 2020) com un dels seus pilars fonamentals. L'Estratègia fa una aposta arriscada de cara a 2030 en què planteja reduir la pèrdua de nutrients en un 50 % com a mínim, sense malmetre la fertilitat dels sòls, amb la qual cosa estima una reducció en l'ús dels fertilitzants d'almenys un 20 %.

Si s'enfoca tot això a les pràctiques de fertilització, hom plantejaria reduir o fins i tot suprimir les aportacions de fertilitzants i, d'aquesta manera, ben segur s'aturaria, o almenys minvaria, l'impacte que comporten aquestes pràctiques. Ara bé, cal tenir ben present la incapacitat dels sòls per a mantenir produccions elevades a llarg termini, amb la qual cosa es requereix restituir aquells nutrients que marxen amb la collita (llei de la restitució), o bé que es perden degut a la ineficiència de les aplicacions de fertilitzants o com a conseqüència de certes pràctiques agrícoles (MAPA, 2022). Per aquest motiu, si es vol continuar mantenint els nivells de producció d'aliments actuals és totalment necessària aquesta aportació de fertilitzants o esmenes (García-Serrano *et al*., 2010; Blum, 2013). De fet, la població mundial continua creixent i les xifres actuals indiquen que caldrà incrementar aquesta producció en els propers anys sota un escenari cada cop més complex on el canvi climàtic i la reducció dels recursos dificultaran més aquesta tasca. Per tot això, els models productius que es plantegin han de ser més eficients per donar resposta a aquesta urgència alimentària de la resta de segle.

1.2 Plantejament de la tesi i objectius generals

El maneig de la fertilització en sistemes agrícoles mediterranis és molt complex i part de la dificultat de gestió es deu a la dependència en la disponibilitat d'aigua per part dels cultius, que anirà lligada de la pluviometria, de la possibilitat de regar, del tipus de sòls i del maneig agronòmic. Atenent a la pluviometria anual, es poden classificar els secans agrícoles de Catalunya. Bosch-Serra (2010) distingeix 4 categories: secà àrid (<250 mm), secà semiàrid (250-450 mm), secà subhumit (400-700 mm) i secà humit (>700 mm); GENVCE (2011) proposa 3 categories: secà semiàrid (<500 mm), secà subhumit (500-700 mm) i secà humit (>700 mm), però les divideix alhora en 3 subcategories, segons la temperatura mitjana del mes d'abril, com són les zones fredes (<11 ºC), templades (11-13 ºC) i càlides (>13 ºC). Els diferents casos estudiats en el present treball exemplifiquen part d'aquesta diversitat de sistemes agraris, des del punt de vista de la gestió del nitrogen.

1.2.1 Objectius generals

Sota aquest plantejament, l’objectiu general de la tesi consisteix en aprofundir en la millora de la gestió de la fertilització orgànica en cultius extensius, prenent com a base el nitrogen, i atenent a les especificitats existents en diferents sistemes agrícoles mediterranis. En aquest sentit, s’estudien temes diversos que van des dels aspectes productius, l’eficiència del N, l’aplicació d’adobs minerals i esmenes orgàniques, la implementació de rotacions, l’època d’aplicació dels adobs, o els efectes de la fertilització sobre els sòls, entre d’altres.

Els objectius específics són els següents:

- Avaluar diferents estratègies de fertilització orgànica i mineral, en relació amb la producció i l’eficiència en l’ús del N.
- Quantificar l’efecte residual del nitrogen després de l’aplicació de purí porcí, en relació amb les extraccions i els rendiments.
- Avaluar l’efecte de la introducció de colza i pèsol en la rotació amb ordi, en combinació amb diferents estratègies de fertilització, en la producció i en l’ús del nitrogen
- Identificar els beneficis i els riscos associats a diferents estratègies de fertilització en explotacions comercials de conreus extensius en regadiu

1.2.2 Escenaris on s’ha implementat la tesi

Els treballs de la tesi s’han dut a terme en 2 comarques (la Noguera i l’Urgell) amb diferents règims termopluviomètrics, tal i com mostren els diagrames ombrotèrmics (Fig. 1.1).

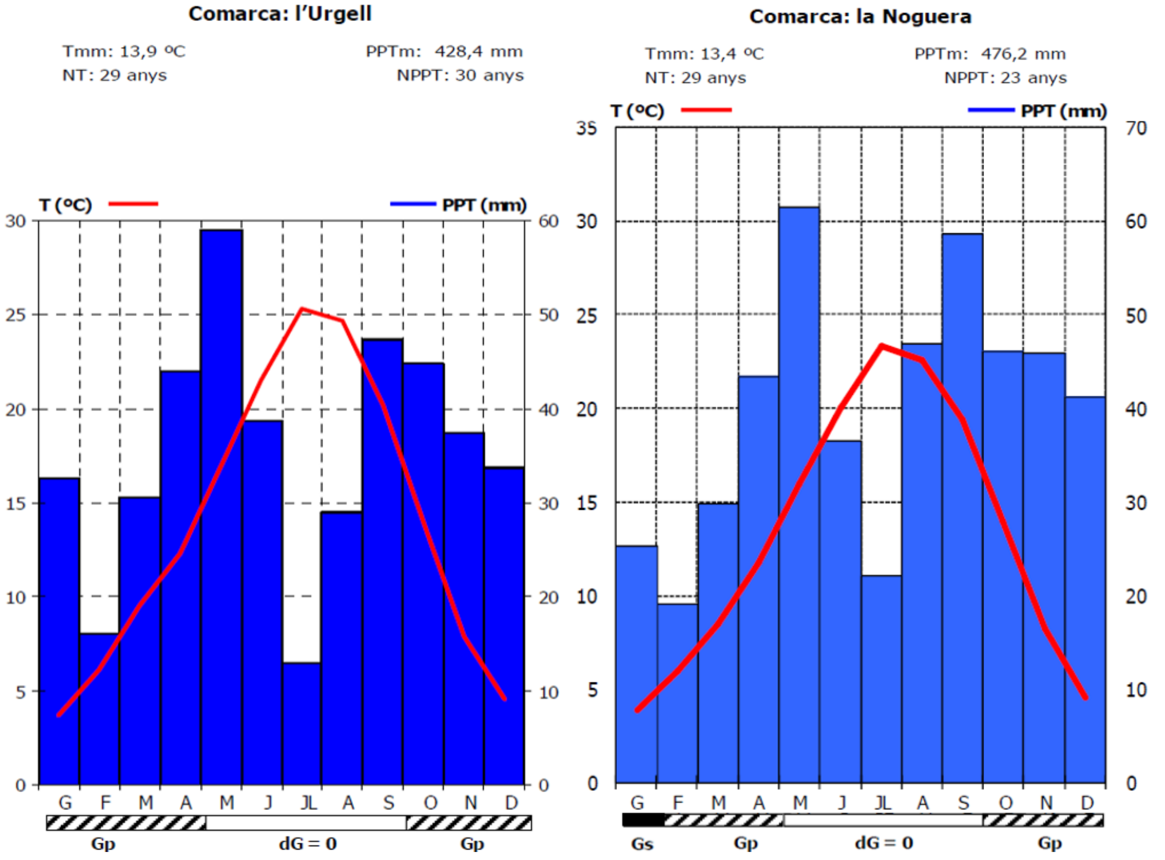

Fig. 1.1 Diagrames ombrotèrmics de les comarques de la Noguera i l’Urgell (SMC, 2019)

En aquest context, es plantegen 3 ubicacions amb escenaris diferents amb un gradient creixent pel que fa a la disponibilitat d'aigua (Fig. 1.2):

- Escenari 1. Camp experimental a llarg termini (iniciat la campanya 1997-98) amb cultius extensius d'hivern (Agramunt). L'estudi se centra en el període 2003-2016. La pluviometria mitjana anual va ser de 428 mm, segons la sèrie climàtica 1971-2000 (Fig. 1.1), i de 392 mm durant el període 2001-2020 (SMC, 2022).
- Escenari 2. Camp experimental a llarg termini (iniciat la campanya 2000-01) amb cultius extensius d'hivern (Oliola). S'hi desenvolupen dos estudis paral·lels, un durant el període 2000-2010, i l'altre durant el període 2013-2020. La pluviometria mitjana anual va ser de 476 mm, segons la sèrie climàtica 1971-2000 (Fig. 1.1), i de 444 mm durant el període 2001-2020 (SMC, 2022).
- Escenari 3. Seguiment a explotacions agrícoles en l'àmbit de tres municipis (Algerri, Castelló de Farfanya i Albesa) amb cultius extensius en una zona de reg per aspersió (a pressió) amb una dotació anual de 6000 m^3/ha i una pluviometria mitjana anual de 379 mm (SMC, 2022). L'estudi se centra en el període 2014-2018.

El primer escenari, amb menys disponibilitat d'aigua, es classificaria dins els secans semiàrids, mentre que el segon, amb una pluviometria anual lleugerament superior de +50 mm, atenent als dos períodes de dades considerats (1971-2000 i 2001-2020), correspondria a la zona llindar entre els secans semiàrids i subhumits, descrites per Bosch-Serra (2010) i GENVCE (2011). Per facilitar la comprensió del document, d'ara en endavant, el segon escenari es considerarà com a secà subhumit, tenint en compte que se situaria a la part baixa d'aquest interval.

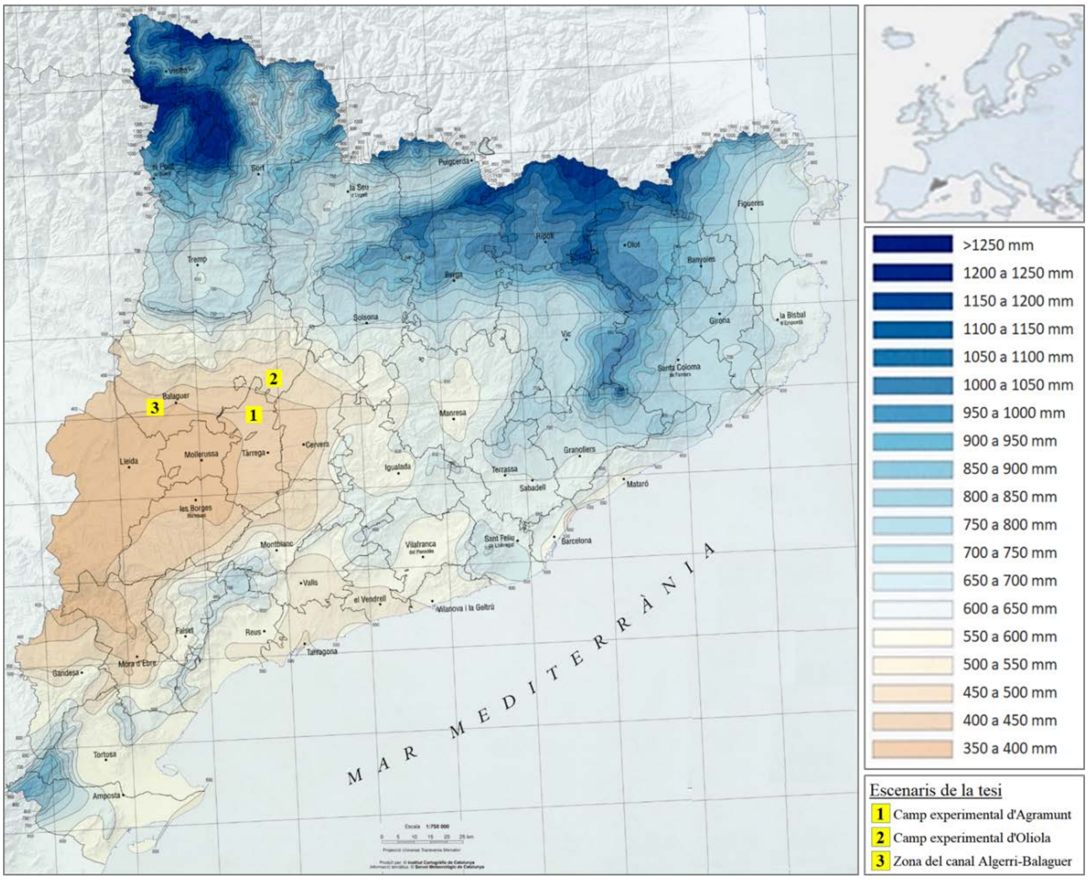

Fig. 1.2 Precipitació mitjana anual (mm) de Catalunya i ubicació dels 3 escenaris on s'ha implementat aquesta tesi (Adaptat de SMC, 2008)

1.2.3 Estructura de la tesi

Aquesta tesi s'estructura en 6 capítols.

El Capítol 1 introdueix al lector en el tema en què s'emmarca la tesi, planteja els objectius i identifica els escenaris on s'han implementat les diferents actuacions, en relació amb la ubicació geogràfica i la disponibilitat d'aigua.

Els capítols 2, 3, 4 i 5 són el nucli del treball i miren de donar resposta als objectius plantejats a la tesi:

- El Capítol 2 se centra en l'avaluació de diferents estratègies de fertilització amb aplicacions continuades d'adobs minerals nitrogenats en comparació amb purins de porcí i llots de depuradora compostats.

- El Capítol 3 estudia l'eficiència i l'efecte residual del nitrogen obtinguts amb l'aplicació de purins porcins.

- El Capítol 4 avalua la implementació de rotacions de cultius com a alternativa a l'aplicació continuada de purins porcins en secans amb monocultiu de cereals.

- El Capítol 5 identifica els riscos i els beneficis potencials associats a diferents estratègies de fertilització que es donen a terme en explotacions agrícoles comercials, amb la caracterització dels sòls i l'evolució del fòsfor en profunditat.

El Capítol 6 presenta la discussió de la tesi i les conclusions generals en relació amb els objectius plantejats.

Referències

Blum, W. E. H. (2013). Soil and Land Resources for Agricultural Production: General Trends and Future Scenarios-A Worldwide Perspective. *International Soil and Water Conservation Research*, *1*(3), 1–14. https://doi.org/10.1016/S2095-6339(15)30026-5

BOE (2022). Real Decreto 47/2022, de 18 de enero, sobre protección de las aguas contra la contaminación difusa producida por los nitratos procedentes de fuentes agrarias. Boletín Oficial del Estado núm. 17, de 20 de enero de 2022, páginas 5664 a 5684. https://www.boe.es/eli/es/rd/2022/01/18/47 Accés 29/10/2022

Bosch-Serra, A.D. (2010). Nitrogen use efficiency in rainfed Mediterranean agriculture. *Encyclopedia of Soil Science*, *1*(1), 1–6. Taylor and Francis. https://doi.org/10.1081/E-ESS-120044989

Cato, & Varro. (1934). On Agriculture. Translated by W. D. Hooper, Harrison Boyd Ash. Loeb Classical Library 283. Cambridge, MA: Publisher: Harvard University Press. ISBN 10: 0674993136

COM (2019). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: The European Green Deal. EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2019:640:FIN Accés 30/06/2022

COM (2020). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system. EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0381 Accés 30/06/2022

DACC (2022). Departament d'Acció Climàtica, Alimentació i Agenda Rural. Ramaderia. Dejeccions ramaderes i fertilitzants nitrogenats. http://agricultura.gencat.cat/ca/ambits/ramaderia/dar_dejeccions_ramaderes_fertilitzants_nitrogenats/dar_zones_vulnerables/ Accés 03/09/2022

DOGC (1998a). Ordre de 22 d'octubre de 1998, del Codi de bones pràctiques agràries en relació amb el nitrogen. Diari Oficial de la Generalitat de Catalunya 2761, 09/11/98. https://portaljuridic.gencat.cat/eli/es-ct/o/1998/10/22/(1) Accés 03/09/2022

DOGC (1998b). Decret 283/1998, de 21 d'octubre, de designació de les zones vulnerables en relació amb la contaminació de nitrats procedents de fonts agràries. Diari Oficial de la Generalitat de Catalunya 2760, 06/11/98. https://portaljuridic.gencat.cat/eli/es-ct/d/1998/10/21/283 Accés 03/09/2022

DOGC (2004). Decret 476/2004, de 28 de desembre, pel qual es designen noves zones vulnerables en relació amb la contaminació de nitrats procedents de fonts agràries. Diari Oficial de la Generalitat de Catalunya 4292, 31/12/2004. https://portaljuridic.gencat.cat/eli/es-ct/d/2004/12/28/476 Accés 03/09/2022

DOGC (2009). Acord GOV/128/2009, de 28 de juliol, de revisió i designació de noves zones vulnerables en relació amb la contaminació per nitrats procedents de fonts agràries. Diari Oficial de la Generalitat de Catalunya 5435, 04/08/09. https://portaljuridic.gencat.cat/ca/document-del-pjur/?documentId=479751 Accés 03/09/2022

DOGC (2015). Acord GOV/13/2015, de 3 de febrer, pel qual es revisen i s'amplien les zones vulnerables a la contaminació per nitrats procedents de fonts agràries. Diari Oficial de la Generalitat de Catalunya 6804, 05/02/15. https://portaljuridic.gencat.cat/ca/document-del-pjur/?documentId=684097 Accés 03/09/2022

DOGC (2019). Decret 153/2019, de 3 de juliol, de gestió de la fertilització del sòl i de les dejeccions ramaderes i d'aprovació del programa d'actuació a les zones vulnerables en relació amb la contaminació per nitrats que procedeixen de fonts agràries. Diari Oficial de la Generalitat de Catalunya 7911, 05/07/19. https://portaljuridic.gencat.cat/eli/es-ct/d/2019/07/03 Accés 03/09/2022

DOGC (2021). Ordre TES/80/2021, de 9 d'abril, per la qual es revisen les zones vulnerables en relació amb la contaminació per nitrats procedents de fonts agràries i s'apliquen les mesures del programa d'actuació a les zones vulnerables. Diari Oficial de la Generalitat de Catalunya 8386, 14/04/21. https://portaljuridic.gencat.cat/eli/es-ct/o/2021/04/09/tes80 Accés 03/09/2022

Erisman, J. W., Sutton, M. A., Galloway, J., Klimont, Z., & Winiwarter, W. (2008). How a century of ammonia synthesis changed the world. *Nature Geoscience*, *1*(10), 636–639. https://doi.org/10.1038/ngeo325

EUROSTAT (2021). Eurostat regional yearbook 2021. Statistical Office of the European Union. https://ec.europa.eu/eurostat/. Accés 15/05/2022

Garcia-Serrano, P., Ruano, S., Lucena, J.J., & Nogales, M. (2010). Guía pràctica de la fertilización racional de los cultivos en España. Parte I. Ed. Ministerio de Medio Ambiente y Medio Rural y Marino. ISBN: 978-84-491-0997-3 https://www.mapa.gob.es/es/agricultura/publicaciones/Publicaciones-fertilizantes.aspx

GENVCE (2011). Grupo para la evaluación de nuevas variedades de cltivos extensivos enm España. Evaluación agrónomica y de la calidad de las nuevas variedades de cebada, trigo blando, trigo duro, triticale, avena y centeno híbrido en España. Campaña 2011/2012. https://genvce.org/productos-genvce/informes/ Accés 31/10/2022

INE (2020). Instituto Nacional de Estadística. Censo Agrario 2020. xplotaciones ganaderas por tipo de ganado y tamaño según unidades ganaderas totales (UGT) https://www.ine.es/jaxi/Tabla.htm?tpx=52773&L=1 Accés 03/09/2022 .

MAPA (1961). Ministerio de Agricultura, Pesca y Alimentación. Censo General Ganadero 1960. Anuario 1961. Fondo documental del Instituto Nacional de Estadística. Accés 02/10/2022

MAPA (1993). Ministerio de Agricultura, Pesca y Alimentación.. Censo General Ganadero 1990. Anuario 1993. Fondo documental del Instituto Nacional de Estadística. Accés 02/10/2022

MAPA (2022). Ministerio de Agricultura, Pesca y Alimentación. Balances de nutrientes en la agricultura española. Año 2019. https://www.mapa.gob.es/es/agricultura/temas/medios-de-produccion/productos-fertilizantes/default.aspx Accés 02/10/2022

NEPA (1969). National Environmental Policy Act of 1969. Council on Environmental Quality Executive Office of the President of the United States of America

OJ (1991). Council Directive 91/676/EEC of 12 December 1991 oncerning the protection of waters against pollution caused by nitrates from agricultural sources. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:31991L0676&from=EN Accés 21/09/2021

OJ (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32000L0060&from=ES Accés 02/06/2022

OJ (2010). Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control). https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32010L0075&from=es Accés 02/10/2022

OJ (2016). Directive 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/ EC and repealing Directive 2001/81/EC. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32016L2284&from=ES Accés 02/10/2022

PRODECA (2019). Promotora d'Exportacions Catalanes. El sector de la Catalunya Agroalimentària. Departament d'Acció Climàtica, Alimentació i Agenda Rural. https://prodeca.cat/ca/sectors/el-sector-de-la-catalunya-agroalimentaria Accés 20/02/2022

SMC (2008). Servei Meteorològic de Catalunya. Atles Climàtic de Cataluya, ed. 2008. Període 1961-1990. https://www.meteo.cat/climatologia/atles_climatic/ Accés 31/10/2022

SMC (2019). Servei Meteorològic de Catalunya. Climatologies comarcals. http://www.meteo.cat/wpweb/climatologia/el-clima-ahir/climatologia-comarcal/ Accés 31/10/2022

SMC (2022). Servei Meteorològic de Catalunya. Generalitat de Catalunya. Disponible en: https://www.meteo.cat/wpweb/climatologia/ Accés 02/05/2022

Capítol 2. Estrategias de fertilización nitrogenada en cereal de invierno y colza en secano semiárido Mediterráneo

2.1 Introducción

La Unión Europea (UE) presentó en 2020 la Estrategia de la Granja a la Mesa (COM, 2020) como una de las iniciativas claves en el marco del Pacto Verde Europeo (COM, 2019) con la finalidad de dirigirse hacia un modelo alimentario más sostenible. Dicha Estrategia aborda, entre otros temas, el uso de los abonos en la agricultura, y marca unos objetivos ambiciosos para el año 2030 de reducción de las pérdidas de nutrientes en un 50 % como mínimo, así como del uso de fertilizantes en al menos un 20 %.

Este doble reto debe afrontarse de maneras muy variadas atendiendo a las casuísticas de cada región. En el caso de España, y en particular de la comunidad autónoma de Catalunya, la disponibilidad de agua, así como la existencia de ganadería intensiva y otros residuos orgánicos serán factores clave que, sin duda, determinarán la estrategia de fertilización y, a su vez, el potencial de cumplimiento de los objetivos europeos citados.

Las tierras de cultivo en Cataluña ocupan 855.706 ha, que equivalen al 26 % de su territorio, de las cuales dos tercios se dedican a cultivos herbáceos y barbecho. El secano predomina en tres cuartas partes, siendo la cebada (*Hordeum vulgare* L.) el cultivo más implantado con 138.209 ha. La colza (*Brassica napus* L.) es una alternativa muy utilizada como rotación en los secanos y cuenta con una superficie cultivada de 10.794 ha (DACC, 2021).

Aunque la pluviometría del territorio catalán es muy variable, pudiendo superar los más de 1200 mm en zonas del Pirineo, ocho de las 42 comarcas existentes registran menos de 400 mm anuales (SMC, 2022). Esta situación de baja disponibilidad de agua es un factor especialmente crítico para la correcta implantación y desarrollo de los citados cultivos, y que influye de manera significativa en el rendimiento (Lampurlanés *et al*., 2016). El rendimiento medio de cebada y colza cultivados en secano correspondiente a las campañas 2016 a 2020 se sitúa en torno a las 3,5 y 2,3 t/ha, respectivamente (DACC, 2022), por lo que las necesidades de N estimadas por hectárea (Ruralcat, 2022) superarían ligeramente, en ambos casos, las 80 unidades fertilizantes.

En cuanto a la ganadería intensiva, Cataluña es una de las regiones NUTS2 de la Unión Europea que concentra más ganado por unidad de superficie. El porcino (*Sus scrofa domesticus*) es el sector más destacado, siendo Cataluña una de las cuatro regiones europeas que superan los 7,5 millones de cabezas (EC, 2022), detrás de la Baja Sajonia (Alemania), Aragón (España) y Bretaña (Francia). La generación de purines en Cataluña fue de 54.830 t N el año 2017, cifra equivalente al 62 % del total de nitrógeno (N) que proviene de deyecciones ganaderas (DARP, 2019). Todo ello conlleva a que la gestión de purines sea una de las cuestiones medioambientales más relevantes.

Así pues, en el interior de Cataluña es frecuente encontrar zonas de muy baja pluviometría y con elevada disponibilidad de purines de porcino que se aplican frecuentemente para la fertilización de los cultivos. No obstante, cabe destacar también el uso de lodos procedentes de estaciones depuradoras de aguas residuales generadas en zonas urbanas. De las 108.600 t de lodos (ms) anuales resultantes en 2017, equivalentes a 4.908 t N, el 93 % tiene como destino final la aplicación al suelo (MAPA, 2016; ACA, 2021), mayoritariamente en cultivos de secano.

Pese a la elevada cantidad de N disponible procedente de estiércoles y de otros residuos como los lodos de depuradora, el consumo de abonos nitrogenados de síntesis se elevó a las 47.606 t N durante la campaña 2017/2018 (ANFFE, 2019).

Por todo esto, la gestión de los nutrientes, y especialmente del N, toma especial relevancia en términos agronómicos, medioambientales y económicos. De los objetivos planteados por la UE, la reducción del uso de fertilizantes está relacionada con un mejor ajuste a las necesidades de los cultivos, aunque también a la mejora de la eficiencia de los nutrientes aplicados (Shepherd & Harrison, 2000). Webb *et al.* (2011) hicieron una revisión muy amplia que incluía trabajos de numerosos autores en la que se identificaron diversas actuaciones y medidas para mejorar la eficiencia de las aplicaciones de estiércoles, destacando las diferencias atribuidas al tipo de estiércol, cultivo o rotación, período de aplicación, tipo de suelo, clima, método de aplicación y tratamiento del estiércol previo.

La hipótesis de este trabajo es que en zonas de limitadas extracciones las aportaciones continuadas de N pueden ajustarse o disminuir respecto a las aplicaciones generales máximas en estos sistemas, ubicados en zonas vulnerables (170 y 120 kg N/ha para fertilizantes orgánicos y minerales, respectivamente) y no vulnerables (190 kg N/ha de fertilizantes orgánicos). El objetivo de este trabajo es determinar la estrategia de fertilización que mejor se adapte a las condiciones de regiones semiáridas.

2.2 Materiales y métodos

2.2.1 Ubicación del experimento

La parcela experimental está ubicada en el término municipal de Agramunt, Lleida, España (41° 46' 31.7" N, 01° 05' 40" E), una zona de clima Mediterráneo continental seco donde la distribución de la precipitación es irregular, con dos máximos en primavera y otoño y un total anual escaso (Fig. 2.1). De estos dos máximos, destaca el de la primavera en la zona de estudio. La pluviometría media registrada durante el período de estudio (2003-2016) fue de 387 mm anuales y de 48 mm entre febrero y marzo, con gran oscilación entre años (201-621 mm y 8-100 mm, respectivamente). Los años considerados como secos, atendiendo a una pluviometría durante el período de elongación del tallo inferior a 50 mm, fueron 2005, 2006, 2007, 2008, 2011, 2012 y 2014. El régimen térmico de la zona es caluroso en verano y frío en el invierno, con una amplitud térmica muy alta. Los valores de evapotranspiración del cultivo de referencia para el período 2007-2016, calculado según Penman-Monteith (Allen *et al.*, 1998), son elevados (1091 mm/año). El período libre de heladas está comprendido entre los meses de mayo y septiembre, ambos incluidos. También son frecuentes años con granizo en primavera pudiendo ocasionar daños en la cosecha, tal y como ocurrió en mayo de 2016.

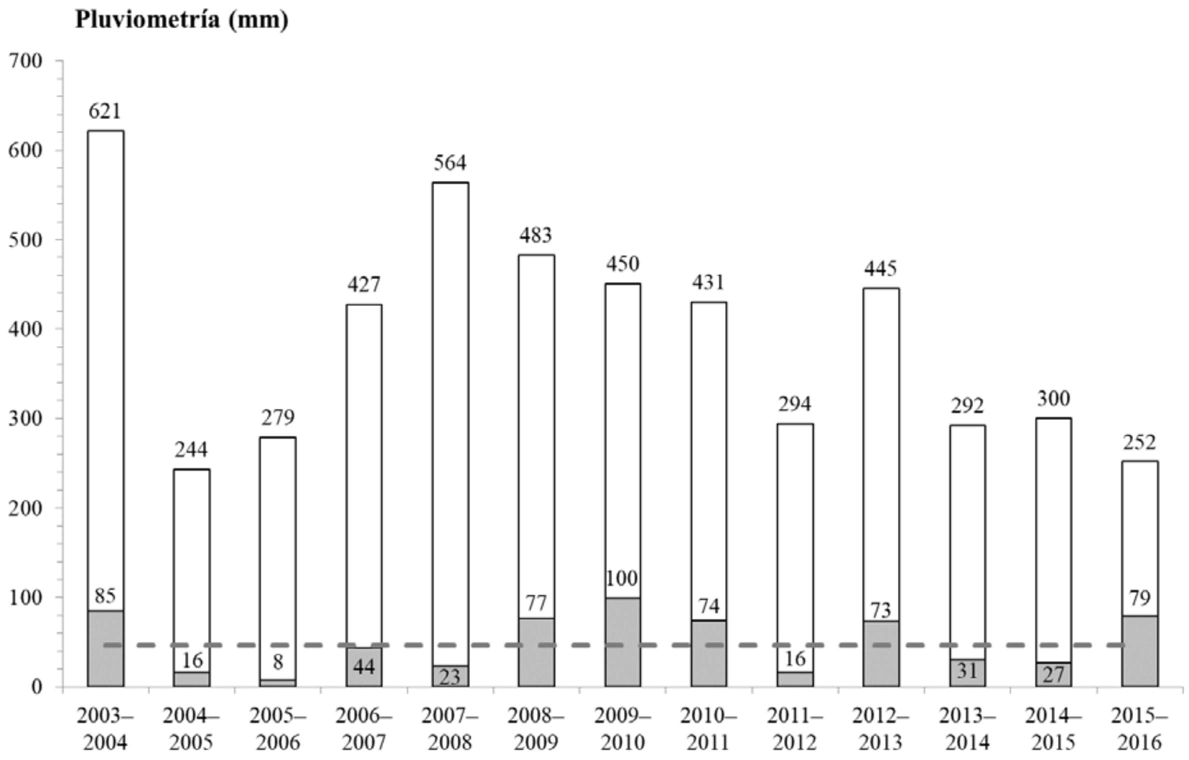

Fig. 2.1 Pluviometría total (mm) de septiembre a agosto (valores en las columnas blancas) y pluviometría registrada en el período de elongación del tallo de febrero a marzo (valores en las columnas grises), correspondiente al período 2003–2004 a 2015–2016. La línea con guiones corresponde al promedio de los datos históricos en el período de elongación del tallo.

2.2.2 Tipo de suelo

El suelo se clasifica como Xerorthent típico (Soil Survey Staff, 2014), muy profundo (>100 cm), bien drenado y sin elementos gruesos. La textura del suelo en los 25 cm superficiales es franca (clasificación USDA). El pH es básico (7,9; 1:2,5 suelo:agua), no salino con conductividad eléctrica moderada (CE 1:5 suelo:agua; 0,33 dS/m a 25 °C), con un alto contenido en carbonato cálcico equivalente (28 %) y unos bajos niveles de materia orgánica al inicio del ensayo (1,9 %).

2.2.3 Diseño del experimento, muestreos y análisis de suelo y planta

Los datos de este trabajo forman parte de un experimento de larga duración (Fig. 2.2) que se inició en la campaña agrícola 1997-98, antes del presente estudio. Este trabajo engloba un total de 13 campañas de cultivo, iniciándose en la campaña 2003-04 y finalizando en 2015-16. Se ha establecido un diseño experimental en bloques al azar, con 3 bloques. El factor principal o tipo de abono en pre-siembra (cinco tratamientos) se cruzó con el factor secundario o abono mineral nitrogenado en cobertera (3 tratamientos). Así pues, los tratamientos previos a la siembra fueron un control sin aportes de N, abono mineral nitrogenado, purín de cerdo de engorde, lodos de depuradora compostados y lodos de depuradora compostados al doble de dosis respecto al tratamiento anterior. El ensayo tenía un total de 45 parcelas experimentales de 7 m de ancho por 23 m de largo.

En las parcelas control se efectuó el muestreo de N nítrico de los primeros 90 cm del suelo previamente a la siembra de los años 2003, 2006, 2009, 2012 y 2016, a excepción del valor de 2009 que corresponde a un muestreo efectuado en el mes de enero. También se tomaron muestras del N nítrico en los 30 y 90 primeros centímetros de suelo de todos los tratamientos durante el inicio (octubre de 2003) y final del ensayo (octubre de 2016). Se utilizó una barrena Edelman de 7 cm de diámetro. Para la determinación del N nítrico se efectuó una extracción de 20±0,5 g de suelo con 50 ml de cloruro potásico 1 M, y el extracto se midió mediante un analizador de flujo continuo, ajustando los cálculos en base a la densidad aparente para cada profundidad. La humedad del suelo se determinó en una sub-muestra mediante secado en horno a 105 ºC hasta peso constante.

Las parcelas se cosecharon anualmente mediante una máquina recolectora convencional y se recogió una muestra de grano de cada una de ellas para su posterior determinación de la humedad mediante secado a 60 ºC. Los datos de rendimiento se presentan ajustados al 12, 12 y 8 % para los cultivos de cebada, trigo y colza, respectivamente.

Fig. 2.2 Fotografía general del campo de ensayo con trigo variedad Soisson *(02/05/2006)*

2.2.4 Aplicación de fertilizantes y enmiendas orgánicas

Las enmiendas orgánicas se aplicaron mediante maquinaria convencional y el abono mineral manualmente. Tras la aplicación, se incorporó al suelo mecánicamente. Con el cultivo ya implantado, a finales de invierno, las parcelas recibieron, mediante aplicación manual, abono mineral nitrogenado (nitrato amónico cálcico del 27 %, nitrosulfato amónico del 26 % o nitrato amónico del 33,5 %) a tres dosis (0, 50 y 100 kg N/ha). Las parcelas control recibieron aportes de fósforo y potasio durante 6 de las 13 campañas para que estos macronutrientes no fuesen limitantes.

2.2.5 Prácticas agronómicas

Durante las 13 campañas se sembró cebada (*Hordeum vulgare* L.) en los años 2003, 2006, 2007, 2010, 2011, 2012, 2014 y 2015, trigo (*Triticum aestivum* L.) en los años 2004, 2005 y 2009, y finalmente colza (*Brassica napus* L.) en el año 2013 (Tab. 2.1). Las prácticas agronómicas siguieron las pautas del agricultor, excepto la fertilización que se ha regido según los tratamientos de fondo y cobertera establecidos en el experimento. Anualmente, se pasó el cultivador para preparar el terreno previamente a la siembra, en general en los meses de septiembre u octubre. La siembra se efectuó entre finales de octubre y principio de noviembre, excepto en el cultivo de colza (año 2014) que se sembró a principios de octubre para alcanzar el estado de roseta antes de la llegada al frío invernal. La cosecha se llevó a cabo entre finales de junio y principios o mediados de julio. Al finalizar la cosecha, los restos de paja fueron generalmente embalados y exportados de la parcela para su venta en el mercado, excepto en aquellas campañas de baja cosecha en las que se incorporó la poca biomasa generada (ej. 2014).

2.2.6 Balance de nitrógeno y eficiencia en el uso del nitrógeno (NUE)

Se ha estimado el balance anual de N como diferencia entre el N aplicado en forma orgánica o mineral (N_{apl}) y el N exportado con la cosecha (N_{exp}), tanto de grano como de paja. En el año 2014 se incorporaron los restos vegetales en el suelo, con lo que se han tenido en cuenta las exportaciones de grano para el cálculo. El N contenido en el grano y la paja de los tres cultivos del estudio se ha calculado utilizando valores de referencia ofrecidos por el departamento competente en materia de agricultura en Cataluña (Ruralcat, 2022).

Se ha calculado el índice de Eficiencia en el Uso del N (en inglés NUE), como resultado del cociente entre Nexp y Napl, expresándose en porcentaje (EU Nitrogen Expert Panel, 2015).

2.2.7 Análisis estadístico

El análisis estadístico de la producción se ha realizado mediante el paquete estadístico R (versión 4.0) (R, 2020). Para facilitar el análisis y la interpretación de los resultados en cebada se consideró un tercer factor que consistió en dos condiciones ambientales: años secos (2007, 2008, 2011, 2012 y 2015) y no secos (2004, 2009 y 2013). La cosecha de cebada correspondiente al año 2016 no se contempló en el análisis estadístico puesto que fue gravemente afectada por granizo. En trigo, el análisis incluyó tres años: 2005, 2006 y 2010. En colza, el análisis de la producción solo consideró el año 2014.

El modelo final de análisis empleado para cada cultivo fue el siguiente: En cebada, los efectos fijos establecidos fueron abonado de fondo, abonado de cobertera y condiciones climáticas (año seco y año no seco). Los efectos aleatorios del modelo fueron los bloques. En trigo, los efectos fijos considerados fueron abonado de fondo, abonado de cobertera y años. Los efectos aleatorios que se involucraron en el modelo fueron los bloques. Finalmente, en colza, los efectos fijos considerados fueron abonado de fondo y abonado de cobertera Los efectos aleatorios del modelo fueron los bloques.

Tab. 2.1 Prácticas agronómicas ejecuta das en el ensayo (campañas 2003-04 a 2015-16)

Campaña	2003-04	2004-05	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16
Cultivo	Cebada	Trigo	Trigo	Cebada	Cebada	Cebada	Trigo	Cebada	Cebada	Cebada	Colza	Cebada	Cebada
Variedad	Hispanic	Soisson	Soisson	Ordalia	Archipel	Montage	Bokaro	-	Gustav	Meseta	Excalibur	Nure	Nure
Fecha de siembra	15/11/03	29/10/04	08/11/05	07/11/06	08/11/07	27/10/08	09/11/09	18/11/10	29/10/11	29/10/12	09/10/13	30/10/14	23/10/15
Dosis de siembra (kg/ha)	190	190	190	190	200-210	200	190	-	190-210	200	60.000*	200	200
Fecha de abonado de fondo													
- mineral	21/11/03	13/10/04	25/10/05	30/10/06	06/11/07	24/10/08	27/10/09	21/10/10	13/10/11	29/10/12	10/09/13	22/10/14	22/10/15
- purín	21/11/03	13/10/04	25/10/05	07/11/06	07/11/07	25/10/08	27/10/09	21/10/10	13/10/11	24/10/12	09/09/13	28/10/14	22/10/15
- lodos	21/11/03	13/10/04	25/10/05	07/11/06	07/11/07	24/10/08	27/10/09	21/10/10	11/10/11	10/10/12	10/09/13	24/10/14	16/10/15
Fecha de abonado de cobertera	23/01/04	03/02/05	07/03/06	07/02/07	15/02/08	10/02/09	18/02/10	09/03/11	20/03/12	26/02/13	12/03/14	20/02/15	23/02/16
Fecha de cosecha	19/07/04	27/06/05	25/06/07	25/06/07	17/07/08	01/07/09	22/07/10	06/07/11	09/07/12	22/07/13	30/06/14	01/07/15	-/06/16

*número de semillas por hectárea

2.3 Resultados

2.3.1 Caracterización de las enmiendas aplicadas

Los purines y los lodos compostados aplicados durante las 13 campañas consecutivas fueron muy variables, tal y como muestran los datos de desviación estándar (Tab. 2.2). La variabilidad en materia seca y en el contenido de N en los purines y los lodos utilizados han comportado ligeras desviaciones en las cantidades de N aplicadas por unidad de superficie (Tab. 2.3). El contenido de N mineral en relación con el N total es muy distinto según se trate de purines o compost de lodos, siendo 2/3 en el primer caso y 1/3 en el segundo. La relación de nutrientes en los dos tipos de enmiendas también es muy dispar, con una relación N:P:K de 3,6:1,0:2,0 en el purín y de 2,1:1,0:1,0 en el compost de lodos.

Tab. 2.2 Valores medios (± desviación estándar) de la composición de los purines y los lodos aplicados en pre-siembra durante el período de ensayo (campañas 2003-04 a 2015-16).

Parámetros	Unidades	Purín	Lodo
Materia seca	% smf*	6,7±3,6	66,0±14,0
Nitrógeno (N) total	% sms**	8,9±3,7	3,0±1,5
Nitrógeno (N) amoniacal	% sms	6,4±3,4	1,1±0,7
N amoniacal / N total	%	68,0±11,0	36,0±10,0
Fósforo (P)	% sms	2,4±0,5	1,4±0,6
Potasio (K)	% sms	4,8±3,0	1,5±1,7

*smf, sobre materia fresca; **sms, sobre materia seca

2.3.2 Rendimientos obtenidos

En el rendimiento, la respuesta a los tratamientos de fertilización se presenta para cada cultivo. En el caso de la cebada (Fig. 2.3 A, Fig. 2.3 D), en los 8 años analizados, no se observó interacción entre la fertilización de fondo y la de cobertera. Tampoco se observa, con independencia del año (seco o no), una respuesta productiva significativa a la fertilización de fondo. La respuesta productiva a la fertilización en cobertera tampoco depende de la pluviometría del año. Las aportaciones más elevadas en cobertera (100 kg N/ha) implican una reducción significativa de la producción. El promedio de cosecha osciló entre 2469 kg/ha y 4000 kg/ha.

El cultivo de trigo (Fig. 2.3 B, Fig. 2.3 E), en los tres años estudiados, sí que mostró interacción entre los diferentes momentos de fertilización y el año. Los rendimientos de los años 2005 y 2006 fueron muy bajos y significativamente inferiores (2182 y 1692 kg/ha, respectivamente) en comparación con el año 2010 (4912 kg/ha). Solamente en 2010 hubo respuesta al abonado, tanto en fondo como en cobertera. En fondo, la no aplicación de fertilizante provocó una disminución del rendimiento (Fig. 2.3 B) y en cobertera la producción del control disminuyó respecto a la aplicación de 50 kg N/ha aunque ambos tratamientos no se diferenciaron de la dosis más alta (Fig. 2.3 E).

En cuanto al cultivo de colza en 2014 (Fig. 2.3 C, Fig. 2.3 F), se obtuvieron diferencias significativas al abonado en fondo y cobertera, pero sin existir interacción entre ambos factores. El promedio de todos los tratamientos resultó ser de 1922 kg/ha. La aplicación de purín en fondo incrementa respecto al control y el mineral, mientras que la aplicación de lodos solamente muestra diferencias significativas respecto al control. El uso de N en cobertera (50 o 100 kg N/ha) resulta imprescindible para incrementar la producción.

2.3.3 Balance de nitrógeno, NUE y nitrógeno mineral del suelo

Los aportes de deyecciones ganaderas (purines) o de fertilizantes orgánicos (lodos) en fondo han generado balances positivos de N en todos los casos, siendo más importantes si iban acompañados de abonado nitrogenado en cobertera (Tab. 2.3). El tratamiento control y el tratamiento mineral sin aporte de N en cobertera, muestran un balance anual negativo. El índice NUE no supera el 60 % cuando se aportan enmiendas orgánicas en pre-siembra (purines), y disminuye en un 25 % con cada aportación de N en cobertera o hasta un 50 % al duplicar la dosis de fondo (lodos) (Tab. 2.3).

En cuanto al contenido de N nítrico en el suelo, se incrementó entre el inicio (N_{ini}) y el final (N_{fin}) del período de ensayo, para todos los tratamientos y en las profundidades 0-30 y 0-90 cm (Tab. 2.3). Los valores de N nítrico correspondientes al tratamiento control oscilaron a lo largo de los años, siendo de 183, 107, 70, 166 y 206 kg $N\text{-}NO_3^-$/ha en los primeros 90 cm, tomados en pre-siembra de los años 2003, 2006, 2009, 2012 y 2016, respectivamente, a excepción del valor de 2009 que corresponde a un muestreo efectuado en el mes de enero.

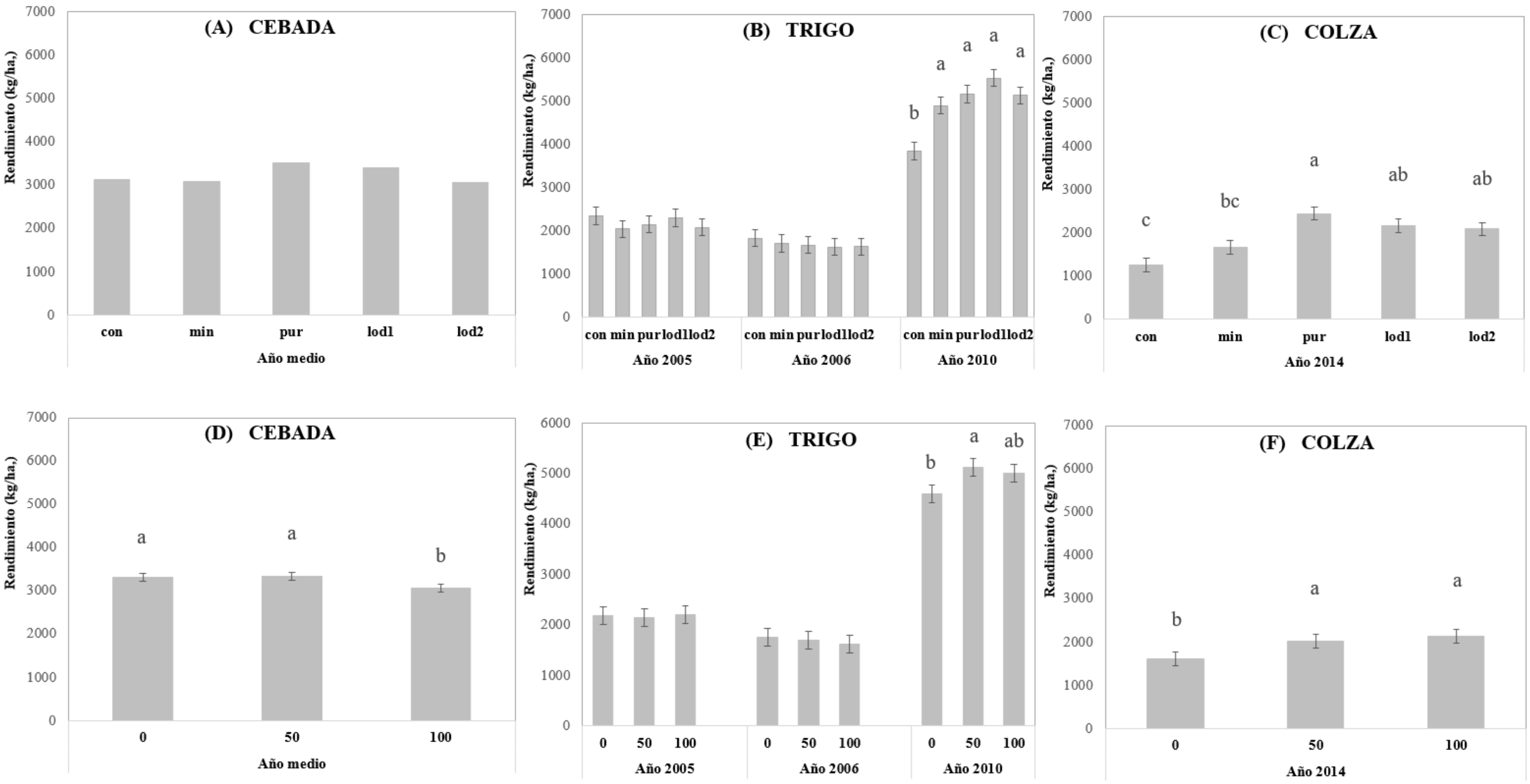

Fig. 2.3 Rendimientos medios para cebada (A y D, en valor medio de 8 campañas), trigo (B y E, en 2005, 2006 y 2010) y colza (C y F, en 2015) en función del tratamiento de pre-siembra (gráficos superiores A, B, C) (con, control; min, mineral; pur, purín de cerdo; lod1 y lod2, lodos compostados a dosis baja y alta, respectivamente) y de cobertera (0, 50 y 100 kg N/ha) (gráficos inferiores). La cantidad de N media aplicada en los tratamientos en fondo fue de 0, 30, 141, 176 y 351, respectivamente. Las líneas verticales en cada columna corresponden al error estándar. Las columnas de producciones con letras distintas indican la existencia de diferencia significativa (P < 0,05) entre tratamientos según Tukey.

Tab. 2.3 Valores medios (± desviación estándar) del N anual aplicado (N_{apl}) en fondo y cobertera (kg/ha), del N exportado (N_{exp}), del balance de N como N aplicado (N_{apl}) menos N exportado (N_{exp}), y del índice de Eficiencia en el Uso del N (NUE) durante el período 2003-2016 (kg/ha), y el contenido de N-nítrico 0-30 cm y 0-90 cm (kg/ha) al inicio (N_{ini}) (octubre 2003) y final (N_{fin}) del ensayo (octubre 2016) para cada uno de los tratamientos.

Tratamiento en fondo	**N_{apl} fondo** (kg N/ha)	**N_{apl} cobertera** (kg N/ha)	**N_{exp} cosecha** (kg N/ha)	**Balance N_{apl}-N_{exp}** (kg N/ha)	**NUE N_{exp}/N_{apl}** (%)	**N_{ini} 0-30cm** (kg N-NO_3^-/ha)	**N_{fin} 0-30cm** (kg N-NO_3^-/ha)	**N_{ini} 0-90cm** (kg N-NO_3^-/ha)	**N_{fin} 0-90cm** (kg N-NO_3^-/ha)
Control	0±0	0±0	62±23	-62±23	-	53±38	88±11	183±110	206±50
		50±0	75±31	-25±31	149±63	70±20	155±20	164±41	281±47
		100±0	66±25	34±25	66±25	46±31	217±110	135±66	480±101
Mineral	30±0	0±0	67±27	-37±27	224±91	56±18	149±43	131±33	252±68
		50±0	73±31	7±31	92±39	36±22	98±50	104±55	292±41
		100±0	69±28	61±28	53±22	57±6	209±122	151±53	619±277
Purin	141±31	0±0	81±31	60±41	60±27	58±15	156±16	181±40	281±33
		50±0	81±31	109±40	43±17	53±18	192±6	141±54	403±109
		100±0	76±31	165±41	32±13	54±16	260±123	150±29	689±229
Lodo 1	176±67	0±0	79±32	97±74	50±22	39±34	135±59	147±103	212±100
		50±0	80±33	145±76	38±16	50±17	161±61	191±61	392±121
		100±0	76±34	200±74	29±12	47±19	222±41	124±15	617±167
Lodo 2	351±136	0±0	75±31	276±137	24±10	70±15	204±123	166±45	340±116
		50±0	69±29	332±139	19±8	65±19	231±138	147±44	539±303
		100±0	70±31	381±137	17±8	63±7	247±87	248±77	1104±206

2.4 Discusión

2.4.1 Rendimientos obtenidos

Los rendimientos de cebada y trigo han sido muy variables, en gran parte como consecuencia de las diferencias en la pluviometría entre distintas campañas y una elevada ETo. La baja pluviometría durante períodos críticos para el desarrollo de los cereales de invierno (febrero-marzo), como el de elongación del tallo (Blum, 1998; Ryan *et al*., 2009), ha sido con mucha probabilidad un factor decisivo que ha influido en ciertas campañas dando lugar a rendimientos bajos de cebada (2492 kg/ha, 5 años) y trigo (1974 kg/ha, 2 años). Este condicionante también se habría manifestado en el año de colza (1922 kg/ha). En los años con menos limitaciones de lluvia (2004, 2009 y 2013) se han obtenido medias más elevadas en cebada (4121 kg/ha, 3 años) y trigo (4603 kg/ha, año 2010), con tratamientos que consiguieron alrededor de los 5000 kg/ha en ambos cultivos. Estas producciones concuerdan con datos obtenidos en zonas con condiciones similares por autores como Bosch-Serra *et al*. (2015), Lampurlanés *et al*. (2016) y Plaza-Bonilla *et al*. (2021).

La estrategia de fertilización para cebada no depende del año (Fig. 2.3 A). La no aplicación de fertilizantes podría resultar, *a priori*, una buena estrategia en el corto plazo, puesto que no presenta diferencias significativas en relación con las otras estrategias estudiadas, además de resultar la más económica y la que genera un menor impacto ambiental. Este hecho puede deberse a que, en los años secos, que son muchos, el agua es un factor más limitante que el N (Bosch-Serra, 2010), mientras que, en los años más húmedos, el tratamiento control se nutre del N mineralizado por el suelo (Shakoor *et al*., 2022). Además, en años algo más lluviosos, puede existir un exceso de biomasa que en determinados momentos fenológicos (p. ej. llenado del grano) puede ser demandante de más cantidad de agua de la que el suelo puede subministrar (Bosch-Serra, 2010). Aun así, la recomendación de abonado a largo plazo no debería ser “no fertilizar” por dos motivos fundamentales. El primero de debe al agotamiento de nutrientes del suelo o “minería”, insostenible a largo plazo (García-Serrano *et al*., 2010; Blum, 2013). El segundo es más una cuestión conceptual, puesto que se trata de un razonamiento que difícilmente entraría en los planes de los agricultores, llegando incluso a perder la credibilidad técnica. Por tanto, se aconsejaría efectuar aportaciones puntuales de abono mineral (50 kg N/ha) en cobertera o de enmiendas orgánicas, como purines en pre-siembra. La aplicación elevada de abono mineral en cobertera (100 kg N/ha) no ha mejorado los resultados, por lo que se desaconseja totalmente. En cuanto a los aportes de purín, su aplicación en cobertera (no contemplada en este ensayo) es muy aconsejada en zonas con mayor disponibilidad de agua (Jackson & Smith, 2007; López-Bellido *et al*., 2012; Bosch-Serra *et al*., 2015). Sin embargo, deberían estudiarse en estas condiciones tan secas, puesto que podría ser que no mostrasen diferencias debido a la no existencia de lavado durante el invierno (Angás *et al*., 2006; Fan *et al*., 2010) y a una menor volatilización por la posibilidad de incorporación si se aplican antes de la siembra (Yagüe & Quílez, 2010; Yagüe & Quílez, 2013).

La fertilización de las campañas en que se introdujo trigo en la rotación se ha visto influenciada por el año, tanto en la fertilización previa a la siembra como en la de cobertera (Fig. 2.3 B, Fig. 2.3 E). En los años más secos (2005 y 2006), las producciones no obtuvieron respuesta al abonado, de manera que en campañas de muy escasa pluviometría no es necesario el aporte de fertilizantes. Sin embargo, en condiciones de disponibilidad de agua (2015), se recomienda el aporte de abono en pre-siembra, especialmente purines o compost de lodos a dosis de ~140 y

~170 kg N/ha, respectivamente, o bien, en caso de no tener disponibilidad, aportar una pequeña cantidad de abono mineral nitrogenado en cobertera (50 kg N/ha). El N disponible en el suelo procedente, en parte, de la aplicación del mismo año, del N residual de campañas anteriores (Daudén *et al*., 2004; Cela *et al*., 2011; Yagüe & Quílez, 2013), sumado a la mineralización de la materia orgánica del suelo (Shakoor *et al*., 2022), pueden explicar la elevada respuesta al N durante los años húmedos. A pesar de ello, no debemos olvidar el escenario de cambio climático en el que nos encontramos, en el que se prevén períodos secos con más frecuencia (Abd-Elmabod *et al*., 2020; Marcos-García *et al*., 2017).

En el caso de la colza, se obtuvieron variaciones importantes que oscilaron desde los 684 kg/ha en el control hasta los 2649 kg/ha conseguidos con la aplicación de purín en pre-siembra y un complemento de 50 kg N/ha en cobertera (Fig. 2.3 C, Fig. 2.3 F). Lampurlanés *et al*. (2016) consiguieron valores similares en dos años secos en un ensayo de rotaciones a largo plazo con colza, mientras que la producción se elevó hasta los 4000 kg/ha en otros dos años en los que hubo mayor disponibilidad de agua. La aplicación de enmiendas orgánicas en pre-siembra ha resultado ser una buena estrategia de abonado para este cultivo, destacando la aplicación de purín de porcino con la que se ha obtenido un mayor rendimiento (2444 kg/ha) (Fig. 2.3 C). La aplicación de compost de lodos en exceso no mejora los resultados, y además el exceso de nutrientes aportado conlleva una mayor acumulación de N residual (Tab. 2.3). La aportación de abono mineral antes de la siembra debería evitarse puesto que no se traduce en una mejor producción (Fig. 2.3 C) y empeora la eficiencia en el uso del N (Tab. 2.3). En el caso de no disponer de enmiendas, una buena alternativa puede ser aplicar 50 kg N/ha en cobertera, sin fertilización en pre-siembra. Aportaciones de N superiores (100 kg N/ha) no mejoran el rendimiento, coincidiendo con los resultados de Porter *et al*. (2020). Esta crucífera ha presentado una buena respuesta al abonado nitrogenado tras una campaña previa de elevadas extracciones (cebada), pudiendo explicarse gracias a la elevada capacidad de exploración de sus raíces (Huang, 2000), junto al buen potencial de absorción durante los estadios fenológicos iniciales (Villar *et al*., 2019). No obstante, con tan solo un año de ensayo, puesto que se trata de un cultivo que se utiliza esporádicamente en las rotaciones de secano, es complejo ofrecer una recomendación, por lo que se necesitarían más años para disponer de resultados más sólidos.

2.4.2 Balance de nitrógeno, NUE y nitrógeno mineral del suelo

La aportación de N con las enmiendas orgánicas ha superado, en general, las necesidades de los cultivos. Este hecho se ha traducido en unos balances de N muy positivos (Napl>Nexp) que incrementan con la dosis de fertilizante aplicada, que no han contribuido a una mayor producción en la mayoría de las campañas estudiadas. No obstante, las dosis más bajas (el control y el tratamiento mineral en pre-siembra sin cobertera de N), extraen más N del sistema del que aportan (-62±24 y -37±29 kg N/ha, respectivamente) con un suministro de N que probablemente proviene de la materia orgánica del suelo que en estas condiciones puede llegar a los 100 kg N/ha en los primeros 60 cm (Plaza-Bonilla *et al*., 2021; Shakoor *et al*., 2022) y en menor caso de la deposición atmosférica (Holland *et al*., 2005; Liu *et al*., 2006; Robertson & Vitousek, 2009).

Siguiendo el criterio planteado por el Panel de Expertos en N de la UE (EU Nitrogen Expert Panel, 2015), el indicador NUE muestra valores dentro del rango aceptable (50-90 %) tan solo para los tratamientos de purín y compost de lodo sin cobertera de N, con valores de 60±28 y 50±21 %, respectivamente. En el resto de casos, el valor NUE desciende bruscamente.

Se detectan datos puntuales (Tab. 2.3) que detallan la acumulación de N en todos los tratamientos y en todo el perfil muestreado. Pese a que la evolución de los nitratos debería mostrarse en base a tendencia y no a datos puntuales, puesto que la fluctuación del N nítrico en el suelo es muy variable, se observa la acumulación de N en el suelo tras aplicaciones continuadas por encima de las necesidades de los cultivos.

2.5 Conclusiones

En zonas semiáridas, la precipitación condiciona la respuesta a la fertilización, la cual no se observa hasta que la precipitación supera los 70 mm en los meses de febrero y marzo. Respecto al tipo de fertilizante, en los cultivos evaluados (cebada, trigo y colza), una de las mejores opciones es la utilización de purines en pre-siembra, aunque su aplicación continuada ha supuesto una acumulación del N residual del suelo que debe ser monitorizado. En zonas con menor disponibilidad de deyecciones ganaderas, la aportación de abono mineral en cobertera a dosis de 50 kg N /ha puede ser una alternativa interesante. El estudio indica que la no aportación de N no presenta diferencias significativas respecto a los otros tratamientos en gran parte de los años estudiados en los cultivos de cebada y trigo. Sin embargo, esta opción constriñe las producciones en años húmedos y supondría una minería de recursos a largo plazo. Para profundizar en las recomendaciones en estas zonas de condiciones climáticas tan extremas, deberían considerarse futuros ensayos con la aplicación de purines en pre-siembra a menores dosis y aplicadas en años alternos.

Referencias

Abd-Elmabod, S. K., Muñoz-Rojas, M., Jordán, A., Anaya-Romero, M., Phillips, J. D., Jones, L., Zhang, Z., Pereira, P., Fleskens, L., van der Ploeg, M., & de la Rosa, D. (2020). Climate change impacts on agricultural suitability and yield reduction in a Mediterranean region. *Geoderma*, *374*, 114453. https://doi.org/10.1016/j.geoderma.2020.114453

ACA (2021). Agència Catalana de l'Aigua. Dades de gestió de biosòlids a Catalunya 2020. Departament d'Acció Climàtica, Alimentació i Agenda Rural. Superfícies i produccions. https://aca.gencat.cat/ca/laigua/gestio-del-cicle-de-laigua/gestio-de-fangs/ Consultado 30/10/2021

Allen, R.G., Pereira, L.S., Raes, D., & Smith, M. (1998). Crop evapotranspiration: Guidelines for Computing Crop Water Requirements. *FAO Irrigation and Drainage Paper 56*. M-56. ISBN 92-5-104219-5 https://www.fao.org/3/x0490e/x0490e00.htm Consultado 30/06/2022

ANFFE (2019). Asociación Nacional de Fabricantes de Fertilizantes. Consumo de fertilizantes en España por comunidades autónomas. http://www.anffe.com/informaci%F3n%20sectorial/evoluci%F3n%20del%20consumo/index.html Consultado 30/10/2021

Angás, P., Lampurlanés, J., & Cantero-Martínez, C. (2006). Tillage and N fertilization. *Soil and Tillage Research*, *87*(1), 59–71. https://doi.org/10.1016/j.still.2005.02.036

Blum, A. (1998). Improving wheat grain filling under stress by stem reserve mobilisation. *Euphytica 1998 100:1*, *100*(1), 77–83. https://doi.org/10.1023/A:1018303922482

Blum, W. E. H. (2013). Soil and Land Resources for Agricultural Production: General Trends and Future Scenarios-A Worldwide Perspective. *International Soil and Water Conservation Research*, *1*(3), 1–14. https://doi.org/10.1016/S2095-6339(15)30026-5

Bosch-Serra, A.D. (2010). Nitrogen use efficiency in rainfed Mediterranean agriculture. *Encyclopedia of Soil Science*, *1*(1), 1–6. Taylor and Francis. https://doi.org/10.1081/E-ESS-120044989

Bosch-Serra, A. D., Ortiz, C., Yagüe, M. R., & Boixadera, J. (2015). Strategies to optimize nitrogen efficiency when fertilizing with pig slurries in dryland agricultural systems. *European Journal of Agronomy 67*, 27–36. https://doi.org/10.1016/j.eja.2015.03.003

Cela, S., Santiveri, F., & Lloveras, J. (2011). Residual effects of pig slurry and mineral nitrogen fertilizer on irrigated wheat. *European Journal of Agronomy*, *34*(4), 257–262. https://doi.org/10.1016/J.EJA.2011.02.003

COM (2019). Comunicación de la Comisión al Parlamento Europeo, al Consejo Europeo, al Consejo, al Comité Económico y Social Europeo y al Comité de las Regiones. El Pacto Verde Europeo. Bruselas. https://eur-lex.europa.eu/legal-content/ES/TXT/?uri=celex:52019DC0640 Consultado 30/10/2021

COM (2020). Comunicación de la Comisión al Parlamento Europeo, al Consejo, al Comité Económico y Social Europeo y al Comité de las Regiones. Estrategia «de la Granja a la Mesa» para un sistema alimentario justo, saludable y respetuoso con el medio ambiente. Bruselas. https://eur-lex.europa.eu/legal-content/ES/TXT/?uri=CELEX%3A52020DC0381 Consultado 30/10/2021

DACC (2021). Departament d'Acció Climàtica, Alimentació i Agenda Rural. Superfícies i produccions dels conreus agrícoles. Any 2020. Servei d'Estadística i Preus Agroalimentaris. Gabinet Tècnic. http://agricultura.gencat.cat/ca/departament/estadistiques/agricultura/distribucio-general-superficie-catalunya/ Consultado 30/04/2021

DACC (2022). Departament d'Acció Climàtica, Alimentació i Agenda Rural. Superfícies, rendiments i produccions dels conreus agrícoles. Anys 2016 a 2020. Servei d'Estadística i Preus Agroalimentaris. Gabinet Tècnic. http://agricultura.gencat.cat/ca/departament/estadistiques/agricultura/estadistiques-definitives-conreus/ Consultado 30/01/2022

DARP (2019). Departament d'Agricultura, Ramaderia, Pesca i Alimentació. Informe de sostenibilitat ambiental del programa d'actuació a les zones vulnerables en relació amb la contaminació per nitrats que procedeixen de fonts agràries. http://agricultura.gencat.cat/ca/detalls/Article/2017_08_DecretdejeccionsRamaderes Consultado 03/10/2021

Daudén, A., Quílez, D., & Martínez, C. (2004). Residual effects of pig slurry applied to a Mediterranean soil on yield and N uptake of a subsequent wheat crop. *Soil Use and Management*, *20*(2), 156–162. https://doi.org/10.1079/SUM2003230

EC (2022). Eurostat Regional Yearbook 2021, Eurostat, Publications Office of the European Union, Brussels. https://doi.org/10.2785/894358

EU Nitrogen Expert Panel (2015). Nitrogen Use Efficiency (NUE) – an indicator for the utilization of nitrogen in agriculture and food systems. Wageningen University, Alterra, PO Box 47, NL-6700 Wageningen, Netherlands

Fan, J., Hao, M., & Malhi, S. S. (2010). Accumulation of nitrate N in the soil profile and its implications for the environment under dryland agriculture in northern China: A review. *Canadian Journal of Soil Science*, *90*(3), 429–440. https://doi.org/10.4141/CJSS09105

García-Serrano, P., Ruano, S., Lucena, J.J., & Nogales, M. (2010). Guía práctica de la fertilización racional de los cultivos en España. Parte I. Ed. Ministerio de Medio Ambiente y Medio Rural y Marino. ISBN: 978-84-491-0997-3 https://www.mapa.gob.es/es/agricultura/publicaciones/Publicaciones-fertilizantes.aspx

Holland, E. A., Braswell, B. H., Sulzman, J., & Lamarque, J.-F. (2005). Nitrogen deposition onto the United States and Western Europe: synthesis of observations and models. *Ecological Applications*, *15*(1), 38–57. https://doi.org/10.1890/03-5162

Huang, B. (2000). Role of root morphological and physiological characteristics in drought resistance of plants. In: Wilkinson, E. Plant-environment interactions. CRC Press, 39-64. https://doi.org/10.1201/9780824746568

Jackson, D. R., & Smith, K. A. (1997). Animal manure slurries as a source of nitrogen for cereals; effect of application time on efficiency. *Soil Use and Management*, *13*(2), 75–81. https://doi.org/10.1111/j.1475-2743.1997.tb00560.x

Lampurlanés, J., Plaza-Bonilla, D., Álvaro-Fuentes, J., & Cantero-Martínez, C. (2016). Long-term analysis of soil water conservation and crop yield under different tillage systems in Mediterranean rainfed conditions. *Field Crops Research*, *189*, 59–67. https://doi.org/10.1016/j.fcr.2016.02.010

Liu, X., Ju, X., Zhang, Y., He, C., Kopsch, J., & Fusuo, Z. (2006). Nitrogen deposition in agroecosystems in the Beijing area. *Agriculture, Ecosystems & Environment*, *113*(1–4), 370–377. https://doi.org/10.1016/j.agee.2005.11.002

López-Bellido, L., Muñoz-Romero, V., Benítez-Vega, J., Fernández-García, P., Redondo, R., & López-Bellido, R. J. (2012). Wheat response to nitrogen splitting applied to a Vertisols in different tillage systems and cropping rotations under typical Mediterranean climatic conditions. *European Journal of Agronomy*, *43*, 24–32. https://doi.org/10.1016/j.eja.2012.05.002

MAPA (2016). Ministerio de Agricultura, Pesca y Alimentación. Balance del nitrógeno 2016: metodología y resultados. https://www.mapa.gob.es/es/agricultura/temas/medios-de-produccion/productos-fertilizantes/default.aspx Consultado 30/10/2021

Marcos-Garcia, P., Lopez-Nicolas, A., & Pulido-Velazquez, M. (2017). Combined use of relative drought indices to analyze climate change impact on meteorological and hydrological droughts in a Mediterranean basin. *Journal of Hydrology*, *554*, 292–305. https://doi.org/10.1016/j.jhydrol.2017.09.028

Plaza-Bonilla, D., Lampurlanés, J., Fernández, F. G., & Cantero-Martínez, C. (2021). Nitrogen fertilization strategies for improved Mediterranean rainfed wheat and barley performance and water and nitrogen use efficiency. *European Journal of Agronomy*, *124*, 126238. https://doi.org/10.1016/j.eja.2021.126238

Porter, M. J., Pan, W. L., Schillinger, W. F., Madsen, I. J., Sowers, K. E., & Tao, H. (2020). Winter canola response to soil and fertilizer nitrogen in semiarid Mediterranean conditions. *Agronomy Journal*, *112*(2), 801–814. https://doi.org/10.1002/agj2.20119

R (2020). Software de estadística R. https://www.r-project.org Consultado 03/05/2020

Robertson, G. P., & Vitousek, P. M. (2009). Nitrogen in Agriculture: Balancing the Cost of an Essential Resource. *Annual Review of Environment and Resources*, *34*(1), 97–125. https://doi.org/10.1146/annurev.environ.032108.105046

Ruralcat (2022). Oficina de fertilització i tractament de dejeccions ramaderes. Departament d’Acció Climàtica, Alimentació i Agenda Rural.

https://ruralcat.gencat.cat/web/guest/oficina-de-fertilitzacio/taules-dades/extraccions-dels-cultius Consultado 03/02/2022

Ryan, J., Ibrikci, H., Sommer, R., & McNeill, A. (2009). *Chapter 2 Nitrogen in Rainfed and Irrigated Cropping Systems in the Mediterranean Region* (pp. 53–136). https://doi.org/10.1016/S0065-2113(09)04002-4

Shakoor, A., Bosch-Serra, À. D., Lidon, A., Ginestar, D., & Boixadera, J. (2022). Soil nitrogen dynamics in fallow periods in a rainfed semiarid Mediterranean system. *Pedosphere,32*. https://doi.org/10.1016/j.pedsph.2022.06.051

Shepherd, M.A., & Harrison, R. (2000). Managing organic manures —is the closed nitrogen cycle achievable? *Aspects of Applied Biology*, *62*, 119–124

SMC (2022). Servei Meteorològic de Catalunya. Generalitat de Catalunya. https://www.meteo.cat/wpweb/climatologia/ Consultado 02/05/2021

Soil Survey Staff (2014). Keys to Soil Taxonomy. USDA-Natural Resources Conservation 556 Service, Washington D.C

Villar, N., Aranguren, M., Castellón, A., Besga, G., & Aizpurua, A. (2019). Soil nitrogen dynamics during an oilseed rape (*Brassica napus* L.) growing cycle in a humid Mediterranean climate. *Scientific Reports*, *9*(1), 13864. https://doi.org/10.1038/s41598-019-50347-1

Webb, J., Sorensen, P., Velthof, G. L., Amon, B., Pinto, M., Rodhe, L., Salomon, E., Hutchings, N., Burczyk, J., & Reid, J. E. (2011). Study on variation of manure N efficiency throughout Europe. (Final report). AEA Technology plc. http://ec.europa.eu/environment/water/water-nitrates/pdf/Man_N_Eff_Final%20Report.pdf Consultado 21/01/2015

Yagüe, M. R., & Bosch-Serra, A. D. (2013). Slurry field management and ammonia emissions under Mediterranean conditions. *Soil Use and Management*, *29*(3), 397–400. https://doi.org/10.1111/sum.12061

Yagüe, M. R., & Quílez, D. (2010). Direct and residual response of wheat to swine slurry application method. *Nutrient Cycling in Agroecosystems*, *86*(1), 161–174. https://doi.org/10.1007/s10705-009-9280-9

Capítol 3. Residual nitrogen effects from pig slurry fertilization of rainfed cereals in a Mediterranean area

3.1 Introduction

Manure has been applied for centuries to crops to replace the lost nutrients due to cultivation and for long it has been known the effects of the applied manure to the crops growth years after the application. Precise knowledge of the nature of the residual effects and its quantification has becoming more and more important along agricultural systems have become more intensive, specialized and concentrated; they need quantitative information in order to adjust fertilization to crop needs, maximizing yields and avoiding unwanted effects to the environment.

Reactive N has surpassed by large the Planet boundaries although some authors (de Vries *et al*., 2013) have questioned several points of this. To increase sustainability there is need to increase N use efficiency (NUE). The EU Nitrogen Expert Panel (2015) has proposed to define NUE in terms of output/input as a tool to assess the sustainability of agricultural systems. In relation to the efficient use of N fertilizers, the European Commission has set up very ambitious objectives in its Communication *Farm to Fork* (COM, 2020). So there is need to use much more efficiently the N fertilizers, specially the organic ones which, at field level, are much less efficient.

Spain is the main pig producer country in the EU-28 with 29.2 million of heads, which represents one fifth of the European pig population (EUROSTAT, 2017). Half of this production is concentrated in two Northern Spanish regions, Catalonia and Aragon, where slurries are mainly used as fertilizers in herbaceous crops. Furthermore, these regions hold all their animal dejection pressure in the 14.5 % of Spanish cultivated land (INE, 2017). Thus, the improvement of N use efficiency from manures in agriculture has become a challenge regarding environment and farm sustainability. Fields are manured every year in many areas, especially in the ones with high animal densities.

The manure composition ratios NH_4^+-N/organic-N and C/N are commonly considered to evaluate N availability from manures (Beauchamp & Paul, 1989). Nevertheless, these ratios may underestimate the real N availability used in manure-based fertilization schedules, because of the mineralization of organic-N along different cropping seasons and the unused mineral-N (Cela *et al*., 2011). Several approaches have been used to estimate the N released from manure. Pratt *et al*. (1973) developed the concept of decay series that indicates the amount of available N after manure applications in the following annual cropping seasons. The recovery method (Schröder *et al*., 2007), the fertilizer equivalence method (Klausner *et al*., 1994) or the use of labeled 15-N manure (Sorensen & Thomsen, 2005) have also been used to describe how N is released over the years. Modeling is often used to explain N dynamics in different scenarios (Klausner *et al*., 1994; Schröder *et al*., 2005; Schröder *et al*., 2007). However, several authors indicate that some of those methods may underestimate the available N, especially in dryland areas (Daudén *et al*., 2011; Yague *et al*., 2013). Thus, a residual effect (RE) after manure applications should be considered as crucial to determine the amount of available N and increase the manure-N efficiency (Webb *et al*., 2011).

Nitrogen RE from manure, and particularly liquid manure, is not easy to measure in short-term experiments because of the small RE obtained. The low ratios of organic-N *vs*. total-N in PS make the RE difficult to evaluate, which explains there are not so many studies on that issue. The trouble increases in rainfed crop areas, where high rainfall variability may cause large yield changes. Besides, most of the authors have worked under Central and Northern European conditions (Berntsen *et al*., 2007) or with irrigation systems (Yagüe & Quílez, 2013).

Consequently, long-term experiments implemented in drier areas are needed to estimate the availability of N beyond the year of PS application.

The objective of this long term study was to estimate the RE of PS in winter cereals in a rainfed Mediterranean area, and its equivalent when comparing with mineral N (MN) fertilization in a for a very long time non manured field.

Our hypothesis is that the use of PS in semiarid rainfed areas with Mediterranean climate provides N to crop in years thereafter application, although the effect could not last more than three years.

3.2 Materials and methods

The experiment was conducted over 10 years, from October 2000 to June 2010, in a semiarid Mediterranean rainfed area, located in Oliola (NE of Spain, 41º 52' 31'' N, 1º 9' 8'' E, altitude 440 m a.s.l.). Annual rainfall averages 476 mm. The soil is classified as Typic Xerofluvent (Soil Survey Staff, 2014). At the beginning of the experiment, the topsoil (0-30 cm) had a silty loam texture, pH was 8.2 (1:2.5, soil: distilled water) with a calcium carbonate equivalent content of 300 g/kg. The electrical conductivity (1:5, soil: distilled water) was below 0.2 dS/m at 25 ºC, the organic matter content (Walkey Black method) was 15 g/kg, the available Olsen phosphorus was 17 mg/kg, and the ammonium acetate extractable potassium was 76 mg/kg. Soil rooting depth is large (>100 cm). The soil mineral N content was 41 kg NO_3^--N/ha from 0-30 cm, and 72 kg NO_3^--N/ha from 0-90 cm.

3.2.1 Experimental design and agronomic management

It was ensured that no manure had been applied for a long period of years before the establishment of the trial. Annual crops were sown under rainfed conditions following a typical winter cereal rotation of barley (*Hordeum vulgare* L.) with wheat (*Triticum aestivum* L.) plus one-year fallow (Tab. 3.1). Fallow was introduced as a set-aside former regulation of the European Common Agricultural Policy lasting from 1992 to 2008. Winter cereals were sown at early November, and harvested at the end of June (Tab. 3.1). Cereal straw was annually removed from the field and the stubble was buried by tillage.

Tab. 3.1 Sowing and harvesting crop dates (dd/mm/yy) during the 10-yr experimental period for the different crops.

	Growing season									
	2000–2001	**2001–2002**	**2002–2003**	**2003–2004**	**2004–2005**	**2005–2006**	**2006–2007**	**2007–2008**	**2008–2009**	**2009–2010**
Crop†	B	B	W	B	B	W	B	F	W	B
Sowing	05/11/00	08/11/01	31/10/02	30/10/03	16/11/04	04/11/06	04/11/06	-	10/11/08	03/11/09
Harvesting	18/06/01	28/06/02	26/06/03	26/06/04	01/07/05	27/06/06	26/06/07	-	04/07/09	01/07/10

† B,Barley; F,Fallow; W,Wheat

The experiment was a randomized complete blocks design with nine treatments that were replicated three times. The treatments (Tab. 3.2) included three PS doses, five MN doses, and a control (no N applied). Single applications of PS at doses of 20, 40 or 80 m^3/ha were applied at sowing every four years in order to account for the RE (Tab. 3.2). The MN treatments were annually applied at doses of 30, 60, 90, and 150 kg N/ha at sowing and at cereal tillering, split as it follows: 0-30, 30-30, 30-60, and 30-120 kg N/ha (sowing-tillering). Ammonium nitrate (33.5 % N) was used as fertilizer. In the initial four cropping seasons (from 2000 to 2004), annual doses of PS were annually complemented with 60 kg N/ha as ammonium nitrate (33.5 % N) at cereal tillering according to traditional management practices. Experimental plots were 12 m long and 7 m wide for the control and MN, while the rest of plots were 20 m long and 12 m wide.

Pig slurry was spread using a conventional splash-plate system and incorporated into the soil by disc-harrowing within 24 hours after spreading, and MN was applied by hand and incorporated to the soil too. Control and MN treatments received annual complements of 42 kg P, and 89 kg K/ha at sowing.

Composite soil samples were obtained with a hand auger before fertilizer applications at three depths: 0 to 30 cm, 30 to 60 cm, and 60 to 90 cm. These soil samples were stored at 4 ºC until nitrate content was analyzed by ionic chromatography after nitrate extraction with demineralized water. Slurries were annually sampled from each tank and analyzed to quantify the actual amount of N applied (Tab. 3.3). A total of 24 slurry samples were obtained and analyzed along the 10-yr trial.

Tab. 3.2 Annual mineral nitrogen (MN) and single pig slurry (PS) treatments, and residual effect (RE) to be accounted from 2000/2001 to 2009/2010 cropping seasons.

Treatment	**2000–2001**	**2001–2002**	**2002–2003**	**2003–2004**	**2004–2005**	**2005–2006**	**2006–2007**	**2007–2008†**	**2008–2009**	**2009–2010**
MN	0+30	0+30	0+30	0+30	0+30	0+30	0+30	0	0+30	0+30
(kg N/ha) ‡	30+30	30+30	30+30	30+30	30+30	30+30	30+30	0	30+30	30+30
	30+60	30+60	30+60	30+60	30+60	30+60	30+60	0	30+60	30+60
	30+120	30+120	30+120	30+120	30+120	30+120	30+120	0	30+120	30+120
PS	20§	RE1¶	RE2	RE3	20	RE1	RE2	0	20	RE1
(m^3/ha)	40	RE1	RE2	RE3	40	RE1	RE2	0	40	RE1
	80	RE1	RE2	RE3	80	RE1	RE2	0	80	RE1
	0	20	RE1	RE2	RE3	20	RE1	0	RE3	20
	0	40	RE1	RE2	RE3	40	RE1	0	RE3	40
	0	80	RE1	RE2	RE3	80	RE1	0	RE3	80
	0	0	20	RE1	RE2	RE3	20	0	RE2	RE3
	0	0	40	RE1	RE2	RE3	40	0	RE2	RE3
	0	0	80	RE1	RE2	RE3	80	0	RE2	RE3

† Fallow period.

‡ MN treatment was applied as ammonium nitrate (33.5 % N). First number indicates the amount of N applied at sowing and the second one the amount applied at cereal tillering (kg N/ha).

§ Doses of PS at rates of 20, 40 and 80 m^3/ha applied at sowing.

¶ The grey shaded areas represent the accounted RE in the first (RE1), second (RE2) and third (RE3) year after the PS application.

In the initial four cropping seasons (from 2000 to 2004), annual doses of PS were annually complemented with 60 kg N/ha as ammonium nitrate (33.5 % N) at cereal tillering, according to traditional management practices. From 2004 onwards no additional mineral N was added at tillering.

Tab. 3.3 Chemical parameters (over fresh weight) of pig slurry (PS) applied at sowing from 2000/2001 to 2009/2010 growing seasons

Parameter	**2000–2001**	**2001–2002**	**2002–2003**	**2003–2004**	**2004–2005**	**2005–2006**	**2006–2007**	**2007–2008**	**2008–2009**	**2009–2010**	**Mean**
pH (1:2.5)	8.0	7.7	7.8	9.1	8.7	8.6	8.3	†	8.2	8.7	8.3
DM, g/kg	83	35	105	79	94	109	78	†	80	93	84
Total N, ‡ gN/kg	8.3	4.7	6.8	6.3	8.8	8.9	8.1	†	7.3	6.7	7.7
NH_4^+-N, §‡ gN/kg	6.1	3.6	4.2	4.1	6.1	6.9	5.0	†	5.4	5.0	5.4

†No data because no fertilization took place in the fallow period

‡Kjeldahl method (APHA, 2012)

Grain yield (GY) of each plot was annually obtained with a cereal micro-plot harvester of 1.5 m wide. The yield biomass was measured by drying at 60 ºC and its N content was determined by Kjeldahl method (Umbreit & Bond, 1936). Grain yield was adjusted to 0 % moisture.

3.2.2 Residual effect

The residual N effect (RE) of the PS applied on subsequent cropping seasons was determined from the GY and the whole plant N uptake (WPNU). The experimental design allowed to quantify the first (RE1), second (RE2), and third (RE3) year RE (Tab. 3.4). The RE1 was measured on non-fertilized plots in 2002, 2003, 2004, 2006, 2007, and 2010; the RE2 in 2003, 2004, 2005, 2007, and 2009; and the RE3 in 2004, 2005, 2006, 2009, and 2010, as it is shown in Tab. 3.2.

The availability of residual N from single PS applications was calculated by using the fertilizer equivalence method, which consists of dividing a fertilizer N equivalent (FNE) value to the total amount of applied manure N (Muñoz *et al*., 2004), as shown in Eq.[1].

$$RESIDUAL \;\; N\left(\%\right) = \frac{Fertilizer\ N\ equivalent}{Total\ applied\ manure\ N}\ x\,100 \qquad [1]$$

The FNE value is the amount of mineral N fertilizer required to obtain the same GY or WPNU achieved with the manure N application (Muñoz *et al*., 2004; Schröder, 2005). The GY and WPNU response curves to mineral N application (Tab. 3.4) were used to obtain the FNE from single PS applications (year *i*) on the subsequent years (year *i*+1, year *i*+2, year *i*+3) (Cusick *et al*., 2006). The RE1 was calculated as the FNE in year *i+1* divided by the total-N from PS applied in year *i*. The RE2 was calculated as the FNE in year *i+2* divided by the total N from PS applied in year *i*. The RE3 was calculated as the FNE in year *i+3* divided by the total-N from PS applied in year *i*.

3.2.3 Nitrogen Use Efficiency

Nitrogen Use Efficiency (NUE) was estimated for each PS treatment and year following the proposal of the EU Nitrogen Expert Panel (2015), as the quotient between N output (WPNU) and input (N from PS).

3.2.4 Statistical analysis

The package SAS v9.4 (SAS, 2002) was used for the statistical analysis. The calculations to estimate the GY and WPNU mineral N response curves were carried out using the polynomial regression model. To reject yield data with no yield answer to N applied, because of the dry conditions of the year or other effects, the analysis of variance was determined by using the general lineal models (GLM).

3.3 Results

3.3.1 Climatic conditions

The annual rainfall in the 10-yr experimental period ranged from 279 to 584 mm (Fig. 3.1), and 77 % occurred during the winter cereal growing season (Oct. – Jun.). A severe drought period occurred during 2004–2005 with an accounted rainfall (Oct.–Sep.) of 279 mm, and precipitation below historical records (SMC, 2019) was also observed during the stem elongation period (Mar.–Apr.) in three growing seasons (2002–2003, 2004–2005, and 2005–2006) (Fig. 3.1).

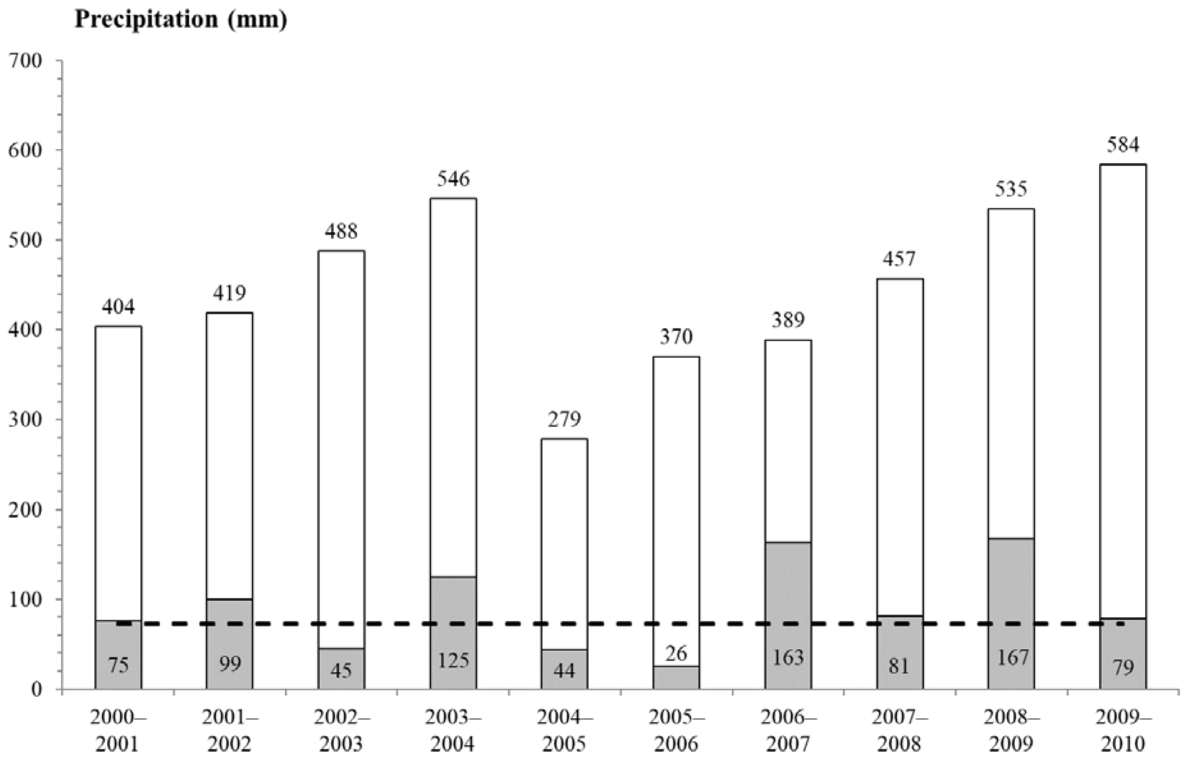

Fig. 3.1 Total precipitation (mm) from October to September (numbers at the top of columns), and rainfall recorded during the stem elongation period from March to April (numbers in the grey columns), for the 2000–2001 to 2009–2010 periods. Dashed line corresponds to the average historical precipitation data at stem elongation. Data was obtained from an automatic meteorological station located at the study site.

3.3.2 Grain yield, nitrogen uptake and nitrogen use efficiency

Grain yield for punctual PS applications averages 3.6 Mg/ha, but shows a very large year variability (1.6 to 5.5 Mg/ha). The average NUE (Fig. 3.2), defined according to the EU Nitrogen Expert Panel (2015), for the year of PS application within the 10-yr period is in the range 0.17–0.40, and increases to 0.24–0.61 if the year after fallow is taken into account. NUE ratios decrease as the dose increase.

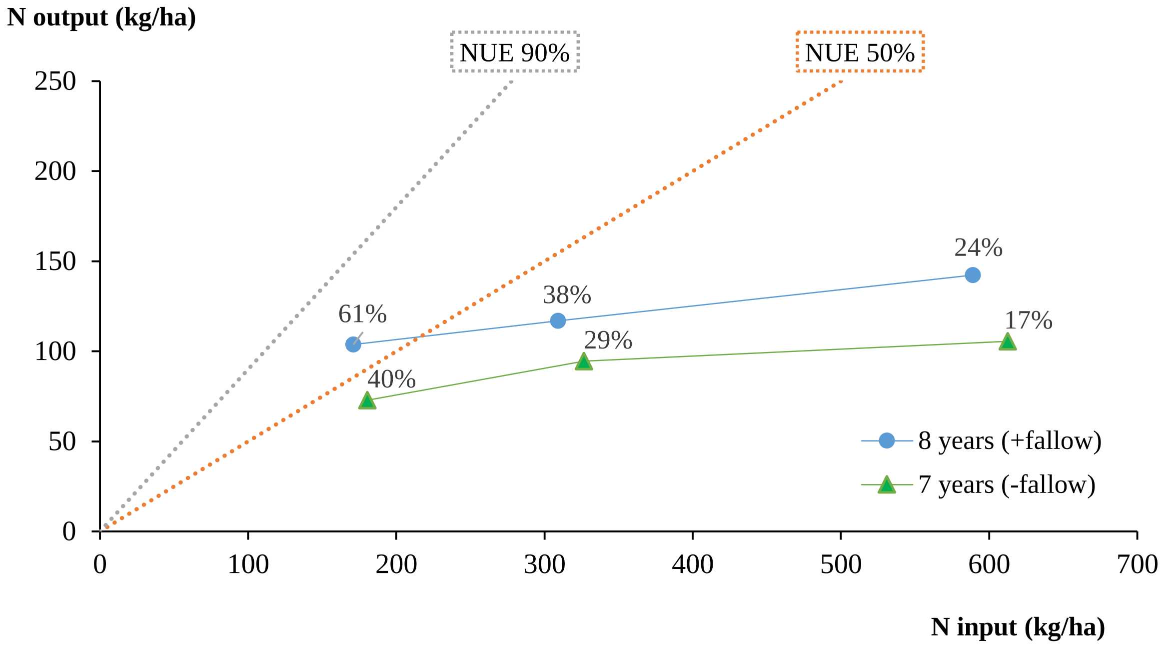

Fig. 3.2 Nitrogen Use Efficiency (NUE) for the years of PS application expressed as the relationship between N input (kg/ha) and N output (kg/ha). The dotted lines (orange and grey) indicate possible target values for NUE (50 and 90%, respectively). Blue circles and green triangles indicate the NUE values at three increasing doses of PS (20, 40 and 80 m^3*/ha) with and without considering the year after the fallow period, respectively.*

In most of the years, GY and WPNU responded positively to MN annual applications (Tab. 3.4) with R^2 values varying from 0.58 to 0.90, and from 0.51 to 0.91, respectively. For GY, data corresponding to 2002–2003, 2004–2005 and 2005–2006 cropping seasons were not taken into account in further calculations because no response to added N was identified due to dry periods during stem elongation (Fig. 3.1). No effect to N fertilization was either obtained after the fallow period in 2008–2009. For WPNU, data from all the cropping seasons was used in the analysis.

Tab. 3.4 Grain yield (GY) and whole plant N uptake (WPNU) response curves to mineral N fertilization applied annually as ammonium nitrate (33.5 %) at rates ranging from 0 to 150 kg N/ha

Growing season	**Polynomial regression**			
	GY	**R^2**	**WPNU**	**R^2**
2000–2001	Y = 2575,12 + 25,0437*X-0,119107*X^2	0,68	Y = 65,38 + 1,07*X-0,00438* X^2	0,76
2001–2002	Y = 2708,08 + 26,716*X-0,136887*X^2	0,58	Y = 56,39 + 0,87*X-0,00326* X^2	0,84
2002–2003	Y = 1765,75 + 15,3512*X-0,0762058*X^2	0,61	Y = 30,66 + 0,54*X-0,00097* X^2	0,83
2003–2004	Y = 2313,07 + 33,9637*X-0,178394*X^2	0,91	Y = 65,34 + 0,69*X-0,00269* X^2	0,56
2004–2005	Y = 1215,7 + 11,8717*X-0,0739383*X^2	0,69	Y = 29,37 + 0,36*X-0,00134* X^2	0,64
2005–2006	Y = 2182,53 + 11,166*X-0,0325398*X^2	0,91	Y = 67,00 + 0,55*X-0,00202* X^2	0,51
2006–2007	Y = 1921,3 + 31,7152*X-0,201552*X^2	0,84	Y= 40,76 + 1,21*X-0,00598* X^2	0,91
2007–2008	Fallow land period		Fallow land period	
2008–2009	Y = 4599,93 + 30,0266*X-0,164394*X^2	0,63	Y = 123,41 + 2,23*X-0,01069* X^2	0,55
2009–2010	Y = 3238,4 + 79,0387*X-0,371552*X^2	0,86	Y = 52,93 + 2,27*X-0,01235* X^2	0,84

Y: Grain yield (GY) in kg/ha or whole plant N uptake (WPNU) in kg/ha

X: kg N/ha applied

3.3.3 Fertilizer nitrogen equivalence

Observed data show the existence of FNE values through the studied period. According to the GY, the higher values (Tab. 3.5) corresponded to the plots that received PS the previous year. As the dose was doubled, the FNE values were also doubled following a clear pattern (i.e. 28.8, 55.8 and 121.3 in 2001–2002). This correspondence between dose and FNE seems to decrease for the second year after the PS application where, as dose was doubled, then it only increased about 1.5. No clear trend is observed three years after the fertilization.

More FNE values are obtained by using the calculation based on WNUP. However, erratic data were calculated during the campaign 2004–2005, with a severe drought and yields below 2 Mg/ha. The rest of results obtained followed a similar pattern, with values slightly lower than the obtained with the GY, when comparing the same years (Tab. 3.5).

Tab. 3.5 Fertilizer N equivalences (FNE) of single pig slurry (PS) applications at rates of 20, 40, and 80 m^3/ha, based in the grain yield (GY), and the whole plant N uptake (WPNU).

Year after PS application	**PS dose**	**N fertilizer equivalent based on GY**					**N fertilizer equivalent based on WPNU**								
	m^3/ha	kg N/ha					kg N/ha								
		2001–2002	**2003–2004**	**2006–2007**	**2009–2010**	**mean**	**2001–2002**	**2002–2003**	**2003–2004**	**2004–2005**	**2005–2006**	**2006–2007**	**2008–2009**	**2009–2010**	**mean**
Year 1	**20**	28.75	2.74	24.31	6.54	15.58	22.31	17.12	0.00	**-**	25.53	11.95	**-**	5.21	13.69
	40	55.81	20.21	36.75	21.92	33.67	39.37	21.74	2.58	**-**	49.85	44.67	**-**	14.27	28.75
	80	121.26	54.88	69.36	31.73	69.31	124.62	46.04	35.44	**-**	240.07	52.11	**-**	23.35	86.94
	mean					**39.52**									**43.12**
Year 2	**20**	**-**	11.18	18.05	**-**	14.61	**-**	14.91	0.00	0.00	**-**	17.76	19.85	**-**	10.50
	40	**-**	12.63	27.17	**-**	19.90	**-**	31.19	3.31	14.78	**-**	9.27	26.26	**-**	16.96
	80	**-**	20.80	40.36	**-**	30.58	**-**	38.01	0.00	**†**	**-**	17.28	46.67	**-**	25.49
	mean					**21.70**									**17.65**
Year 3	**20**	**-**	16.06	**-**	0.00	8.03	**-**	**-**	0.00	26.47	3.47	**-**	27.68	0.00	11.53
	40	**-**	5.64	**-**	6.76	6.20	**-**	**-**	0.71	7.66	23.41	**-**	16.03	6.18	10.80
	80	**-**	19.31	**-**	35.46	27.38	**-**	**-**	6.97	13.15	38.92	**-**	50.07	25.10	26.84
	mean					**13.87**									**16.39**

† lack of N uptake analysis

3.3.4 Residual effects

The experiment demonstrates the existence of RE three years after single applications of PS. Both GY and WPNU results indicated (Tab. 3.6) that available N decreased over time (RE1>RE2>RE3), as it happened with the FNE values (Tab. 3.5).

Data expressed in relation to the total N applied, shows that RE1 is about to 36.18 %, RE2 is 31.19 %, and RE3 is 10.24 %, obtaining 77.60 % three years after the application. Same trend was found in relation to the RE over the WPNU basis, where residual N accounted for a total of 20.84 % of N applied (Tab. 3.6), distributed as 10.9 %, 5.1 %, and 4.8 % for the first, second, and third year after the PS application, respectively. When those values are expressed in relation to the organic N applied, the RE1, RE2 and RE3 rised to 41.41, 16.78, and 18.61 %, respectively, obtaining an accumulated 76.80 % for the whole 3-yr period.

Recovered N during three years after the PS application ranged from 18 to 23 % of total N applied, and from 65 to 90 % of organic N applied (Fig. 3.3). Results show that lower doses of 20 m^3/ha recover, as an average, the highest percentage of N after a 3-yr period, with both methods, GY (22 and 89 % of total N and organic N, respectively) and WPNU (23 and 90 %). Nevertheless, there is no clear trend of a reduction of the RE when doses are doubled to 40 m^3/ha or quadrupled to 80 m^3/ha. As concerns to WPNU calculations of RE, important variations are detected depending on the growing season (Tab. 3.6).

Tab. 3.6 Nitrogen residual effect (RE) of single pig slurry (PS) applications at rates of 20, 40, and 80 m^3/ha, based in the grain yield (GY), and the whole plant N uptake (WPNU), expressed as a percentage of the total-N and organic-N applied.

Year after PS application	**PS dose**	**RE based on GY**					**RE based on WPNU**								
	m^3/ha	% of total N applied					% of total N applied								
		2001–02	**2003–04**	**2006–07**	**2009–10**	**mean**	**2001–02**	**2002–03**	**2003–04**	**2004–05**	**2005–06**	**2006–07**	**2008–09**	**2009–10**	**mean**
Year 1	**20**	10.1	1.1	16.9	6.7	8.7	7.9	9.6	0.0	-	20.8	9.1	-	5.6	8.8
	40	11.3	5.0	12.2	11.7	10.0	7.9	7.3	0.6	-	19.9	14.9	-	7.6	9.7
	80	13.8	7.4	11.0	8.3	10.1	14.4	9.3	4.8	-	42.9	8.3	-	6.0	14.3
	mean					**9.6**									**10.9**
Year 2	**20**	-	6.2	14.7	-	10.4	-	5.2	0.0	0.0	-	14.6	13.2	-	6.6
	40	-	4.2	10.8	-	7.5	-	6.3	1.1	3.7	-	3.6	9.1	-	4.8
	80	-	4.2	7.8	-	6.0	-	4.3	0.0	†	-	3.3	8.5	-	4.0
	mean					**8.0**									**5.1**
Year 3	**20**	-	5.7	-	0.0	2.8	-	-	0.0	14.8	1.5	-	19.6	0.0	7.2
	40	-	1.1	-	2.2	1.7	-	-	0.1	2.6	6.0	-	4.6	2.1	3.1
	80	-	2.2	-	6.4	4.3	-	-	0.8	2.6	5.2	-	7.4	4.5	4.1
	mean					**2.9**									**4.8**
		% of organic N applied					% of organic N applied								
Year 1	**20**	47.1	3.8	58.2	26.5	33.9	36.5	55.6	0.0	-	68.7	31.4	-	21.9	35.7
	40	47.8	15.4	45.8	45.3	38.6	33.7	38.1	1.8	-	65.7	55.9	-	29.5	37.4
	80	55.2	21.0	35.9	32.1	36.1	58.4	42.8	13.7	-	141.4	27.0	-	23.3	51.1
	mean					**36.2**									**41.4**
Year 2	**20**	-	36.3	48.3	-	42.3	-	24.4	0.0	0.0	-	48.0	37.8	-	22.1
	40	-	22.1	35.6	-	28.8	-	26.7	5.8	11.7	-	12.0	24.3	-	16.1
	80	-	19.3	25.5	-	22.4	-	16.8	0.0	-	-	10.8	21.2	-	12.2
	mean					**31.2**									**16.8**
Year 3	**20**	-	26.3	-	0.0	13.2	-	-	0.0	86.0	5.5	-	67.5	0.0	31.8
	40	-	4.8	-	5.2	5.0	-	-	0.6	13.4	18.7	-	17.1	5.3	11.0
	80	-	8.5	-	16.6	12.6	-	-	3.1	11.9	14.7	-	23.5	11.8	13.0
	mean					**10.2**									**18.6**

† lack of N uptake analysis

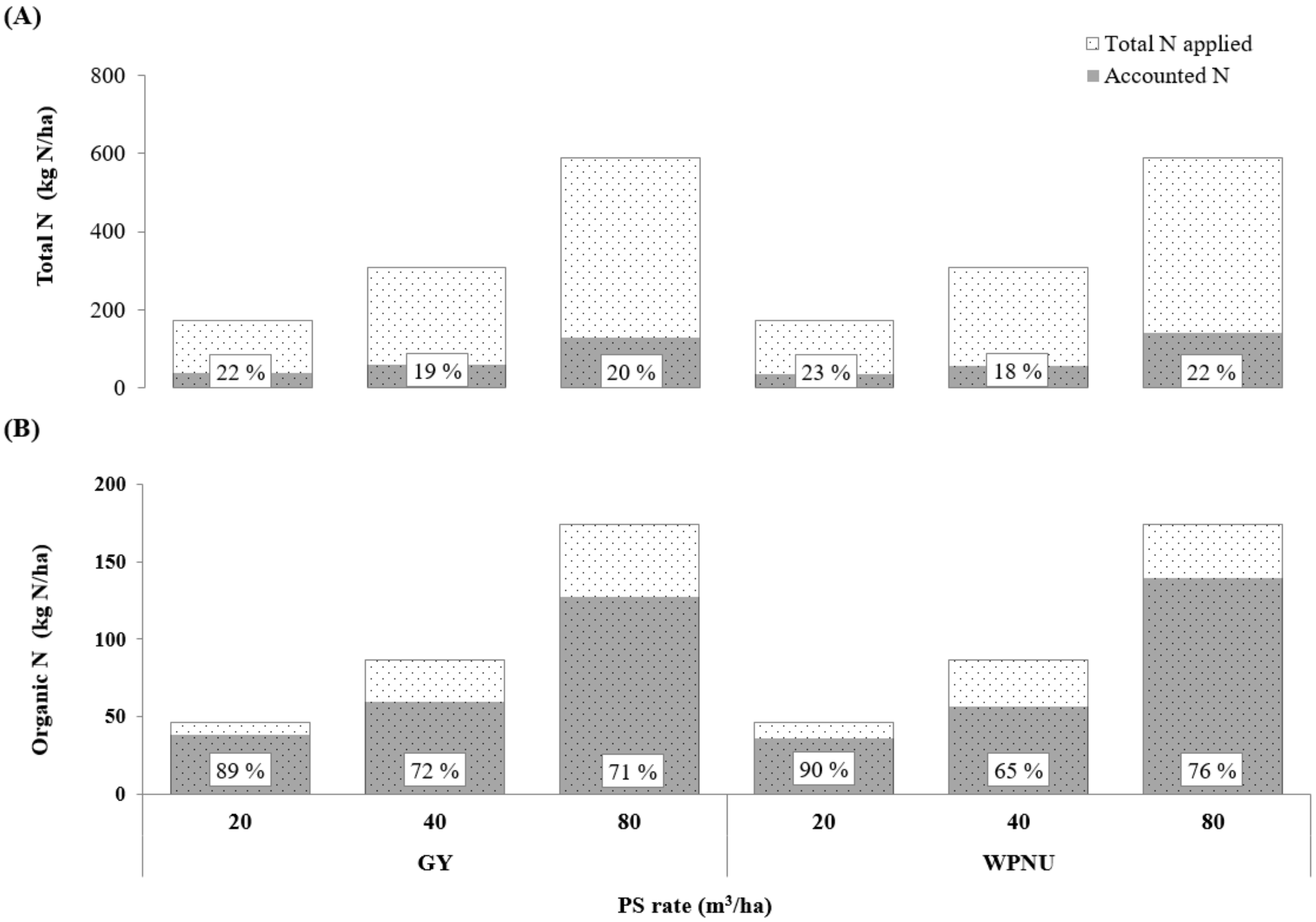

Fig. 3.3 Accumulated N (kg N/ha) accounted for three years after the year of the pig slurry (PS) application, based on grain yield (GY), and whole plant N uptake (WPNU), for three PS doses: 20, 40, and 80 m^3/ha. Values in the upper graphic (A) represent total N application (pointed columns) and residual N accounted for the first three years (grey columns). Values in the bottom graphic (B) represent organic N application (pointed columns) and residual N accounted for the first three years (grey columns). In boxes, the N residual effect accumulated for the three years, expressed in percentage and referred to total-N (A) and organic-N (B) applied with PS.

3.4 Discussion

3.4.1 Crop yield, nitrogen uptake and nitrogen use efficiency

Grain yields in this experiment were around 3.6 Mg/ha, lower to other experiments from temperate Northern Europe, where RE effects of slurries have been investigated (Sorensen & Thomsen, 2005; Pedersen *et al*, 2021). Annual and monthly droughts have been registered during the trial period (Fig. 3.1), which constrained maximum yields of three campaigns to 2.5, 1.7 and 3.1 Mg/ha (Tab. 3.4). These values are lower than data recorded in the same period in the EU-28, where average yields varied from 4 to 5 Mg/ha in barley, and from 5 to 6 Mg/ha in wheat, and far away from the 7.5 Mg/ha for barley and 7.2 Mg/ha for wheat, under irrigated conditions in closer irrigated areas with no water limitation (DACC, 2022). As a consequence, N response on yields is fully dependent on rainfall in rainfed Mediterranean conditions. Nevertheless, results indicated a positive N effect on GY and WPNU (Tab. 3.4). A polynomial regression model was performed to adjust the response function, while other authors used linear-plateau equations (Yagüe & Quílez, 2010), or the Mitscherlich model (Klausner *et al*., 1994). Due to rainfall variability (Fig. 3.1), the N application rate to optimize yields ranged from 79 to 106 kg N/ha, higher rates led to a yield decrease. However, maximum WPNU values were obtained with slightly higher N fertilizer rates (92 to 136 kg N/ha), as lack of water in the last growing stages constrains ear development from tillers and a lot of N remains in straw.

NUE in this experiment for the lower PS dose is higher than 61 % considering the year after fallow, and 40 % if this year is not considered. However, technical improvements as localized PS application or spring PS application have demonstrated (Yagüe & Bosch-Serra, 2013, Bosch-Serra *et al*., 2015) that the efficiency may be improved in a significant manner without hampering yields. Under these improvements, such cropping systems will fall in the desirable NUE ratios outlined by EU Nitrogen Expert Panel (2015).

3.4.2 Residual effects

Nitrogen RE must be carefully interpreted when manure has a different NH_4^+-N/total-N ratio because it has been found that RE is very much dependent on this ratio (Pratt *et al*., 1973; Schröder *et al*., 2007). Our data showed a high content of NH_4^+-N, similar to data collected in the region by Parera *et al*. (2010), data from Spanish experiments published by Cela *et al*. (2011), Yagüe & Quílez (2010), and the UE-15 average reported by Menzi (2002). Lower ratios are found in the work of Hernández *et al*. (2013), who applied PS with ratio values below 0.60, or Schröder *et al*. (2005), that used cattle slurry with ratios around 0.50.

Although it is identified a positive correspondence between dose of PS and FNE, such trend is not significant when the RE is accounted. Results indicate that lower doses of PS (20 m^3/ha) recover the maximum percentage of the N applied (which is 89 and 90 % of organic N, based on GY and WNUP, respectively). That can be explained because yields and N uptake are limited in Mediterranean rainfed systems, so residual N effects are similar even at higher PS doses (40 m^3/ha and 80 m^3/ha).

The RE accumulated during the 3-yr period after a single PS application (Tab. 3.6) averaged 21 % of total N applied based on GY and WPNU. In most of RE trials, N is only estimated for one or two years after the organic amendment, and just a few authors worked beyond two years.

Schröder *et al*. (2007) accumulated values from 7 to 16 % for untreated cattle slurries in a 3-yr period; and Klausner *et al*. (1994) obtained 11-12 % in a 4-yr period. The explanation of these low accumulated RE may be that under semi-arid conditions N remains in soil because of leaching constrains, although N built-up can be a risk if coincides with heavy erratic rainfall (Jiménez-de-Santiago *et al*., 2019).

The RE1 of 10 % matches the 9 % and 12 % reported by Paul & Beauchamp (1993), and Cusick *et al*. (2006), who used the fertilizer equivalence method by applying PS and dairy manure, respectively. Yagüe & Quílez (2010) indicated higher values (17-14 %), in contrast to the observed by Klausner *et al*. (1994) (7 %), or Sorensen & Thomsen (2005) (2.7 %). Differences in RE between authors could be explained in part by the composition of manure, which influences N dynamics. As PS and digested slurries contain more NH_4^+–N than dairy manure, less RE would be expected, as suggested Schröder *et al*. (2007). However, comparing our results with literature may lead us to think that differences on crop water demand (double values of evapotranspiration in semi-arid regions), the gradient of rainfall (from about 400 mm to more than 800 mm), and the distribution of water during the crop season (with intense rain episodes in Mediterranean areas), influences the expression of such RE. This fact is corroborated with the low values reported with high NH_4^+–N contents in more humid environments: i.e. Sorensen (2004) reached 3 % in dairy slurries (NH_4^+–N/total–N of 60 %), and Schröder *et al*. (2007) indicated 3 % in the case of digestates of cattle slurry (NH_4^+–N/total–N of 59 %).

Therefore, our results emphasize the Klausner *et al*. (1994) statement that residual N should be determined for each specific regional conditions. The sequence of residual N accounted for the three years that followed the application (Tab. 3.6) corresponded to 10 %, 8 % and 3 % based on GY, and 11 %, 5 % and 5 % based on WPNU, but the total 3-yr RE gives the same result of 21 %. The differences in the second and third year RE may be explained because lack of water in spring reduces the production of successful ears. Thus, a lot of N remains in straw biomass without increasing yields. Values of RE2 are higher than the ones described in references: 2.3 % (Paul & Beauchamp, 1993), 2 % (Klausner *et al*., 1994) or 3 % (Cusick *et al*., 2006). The RE accounted for the third year was still significant with values about 3 and 5 %, referred to the GY and to the WPNU, respectively. Such results are comparable with the obtained by Klausner *et al*. (1994) and Schröder *et al*. (2007), who pointed at 2 and 1-4 %, respectively, for the RE3.

When the residual N is accounted against the organic N fraction, N recovered by barley and wheat over a 3-yr period after the PS application varied between 78 and 77 %, respectively (Tab. 3.6). Such high values do not match with literature: Sorensen & Amato (2002) recovered from 3 to 16 % of the organic N applied one year after the application, and Klausner *et al*. (1994) accounted for only 15-16 % of the organic N fraction in a 4-yr residual period. These important differences may be explained by dried Mediterranean conditions of the area in which the present experiment was set up. Therefore, mineral N, which is the higher proportion of N in PS, may remain in soil further than one growing season, as suggests Sorensen (2004), experimenting immobilization and mineralization processes to appear again in the years after the application. As leaching in these soils occurs only in certain years as a result of some erratic rainy periods (Shakoor *et al*., 2022), high soil nitrates contents are accumulated at sowing from previous single and repeated PS applications (Ortiz *et al*., 2005; Bosch-Serra *et al*., 2015). This reasoning is also supported by Powell *et al*. (2005), who accounted 47 % of labelled N in soil, and only 21 % in crop uptake, after a dairy manure application.

The residual N from PS applications in limited rainfall scenarios must be considered in the fertilization plans. Hence, it is necessary to account for the available N that remains in soil from previous applications or to combine other strategies such as biennial applications (Bosch-Serra *et al*., 2015) to avoid overfertilization (mainly after a drought period) and minimize eventual nitrate underground water pollution.

3.5 Conclusions

Nitrogen RE showed no clear response to the essayed application rates of PS with high annual variation in a cereal rotation experiment lasting 10 years under rainfed Mediterranean in a soil with high water holding capacity. The residual N was larger the first year after the organic fertilization and decreased in the second and third year. The accounted N for the three subsequent years after single PS applications reached, for the optimal dose, in average 22 % of the total-N applied, which represented 90 and 89 % of organic-N, based on WPNU and GY, respectively. Our results indicate that the amount of N available in the subsequent years after the PS application may correspond to the mineralization from the organic-N fraction plus the remaining mineral-N from the current and previous applications.

Residual effect from previous manure applications should be taken into account when establishing fertilizer plans in semiarid regions. It is a significant steep to reach sustainable NUE ratios, avoiding impacts to the environment in areas where there is no possibility of more than one crop per year due to low water availability and erratic rainfall.

References

APHA. (2012). Nitrogen (ammonia): 4500-NH_3 B, preliminary distillation step and 4500-NH_3 C, titrimetric method. In: E.W. Rice, and L. Bridgewater, editors, Standard methods for the examination of water and wastewater, twenty second ed. American Public Health Association, American Water Works Association, Water Environment Federation Washington, D.C. (4)110-111

Beauchamp, E. G., & Paul, J. W. (1989). A Simple Model to Predict Manure N Availability to Crops in the Field. *Nitrogen in Organic Wastes*, 140–149. https://doi.org/10.1016/B978-0-12-323440-7.50017

Berntsen, J., Petersen, B. M., Sørensen, P., & Olesen, J. E. (2007). Simulating residual effects of animal manures using 15N isotopes. *Plant and Soil*, *290*(1–2), 173–187. https://doi.org/10.1007/s11104-006-9150-z

Bosch-Serra, A. D., Ortiz, C., Yagüe, M. R., & Boixadera, J. (2015). Strategies to optimize nitrogen efficiency when fertilizing with pig slurries in dryland agricultural systems. *European Journal of Agronomy 67*, 27–36. https://doi.org/10.1016/j.eja.2015.03.003

Cela, S., Santiveri, F., & Lloveras, J. (2011). Residual effects of pig slurry and mineral nitrogen fertilizer on irrigated wheat. *European Journal of Agronomy*, *34*(4), 257–262. https://doi.org/10.1016/J.EJA.2011.02.003

COM (2020). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system. EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0381 Accessed 30/06/2022

Cusick, P. R., Kelling, K. A., Powell, J. M., & Muñoz, G. R. (2006). Estimates of Residual Dairy Manure Nitrogen Availability Using Various Techniques. *Journal of Environmental Quality*, *35*(6), 2170–2177. https://doi.org/10.2134/JEQ2005.0287

DACC (2022). Departament d’Acció Climàtica, Alimentació i Agenda Rural. Estadístiques definitives de conreus. Gabinet Tècnic. Servei d’Estadística i Preus Agroalimentaris. https://agricultura.gencat.cat/ca/departament/estadistiques/agricultura/estadistiques-definitives-conreus/ Accessed 04/08/2022.

Daudén, A., Quílez, D., & Martínez, C. (2004). Residual effects of pig slurry applied to a Mediterranean soil on yield and N uptake of a subsequent wheat crop. *Soil Use and Management*, *20*(2), 156–162. https://doi.org/10.1079/SUM2003230

De Vries, W., Kros, J., Kroeze, C., & Seitzinger, S. P. (2013). Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. *Current Opinion in Environmental Sustainability*, *5*(3–4), 392–402. https://doi.org/10.1016/J.COSUST.2013.07.004

EU Nitrogen Expert Panel (2015) Nitrogen Use Efficiency (NUE) - an indicator for the utilization of nitrogen in agriculture and food systems. Wageningen University, Alterra, PO Box 47, NL-6700 Wageningen, Netherlands

EUROSTAT (2017). Statistical Office of the European Communities. http://ec.europa.eu/eurostat/web/agriculture/data/database Accessed 06/06/2017

Hernández, D., Polo, A., & Plaza, C. (2013). Long-term effects of pig slurry on barley yield and N use efficiency under semiarid Mediterranean conditions. *European Journal of Agronomy*, *44*, 78–86. https://doi.org/10.1016/J.EJA.2012.09.001

INE (2017). Instituto Nacional de Estadística. Anuario Estadístico de España 2016, http://www.ine.es/prodyser/pubweb/anuarios_mnu.htm Accessed 06/06/2017

Jiménez-de-Santiago DE, Lidón A, Bosch-Serra AD (2019) Soil water dynamics in a rainfed Mediterranean agricultural system. Water 11 (4):799. doi:10.3390/w11040799Klausner, S. D., Kanneganti, V. R., & Bouldin, D. R. (1994). An Approach for Estimating a Decay Series for Organic Nitrogen in Animal Manure. *Agronomy Journal*, *86*(5), 897–903. https://doi.org/10.2134/agronj1994.00021962008600050026x

Menzi, H. (2002). Manure management in Europe: results of a recent survey. In: J. Venglovsky, and G. Greserova. In: Proceedings of the 10th FAO/ESCORENA Network on Recycling Agricultural, Municipal and Industrial Residues in Agriculture (RAMIRAN), Strbske Pleso, Slovak Republic, 14-18 May, 93–102. ISBN 80-88985-68-4

Muñoz, G. R., Kelling, K. A., Powell, J. M., & Speth, P. E. (2004). Comparison of Estimates of First-Year Dairy Manure Nitrogen Availability or Recovery Using Nitrogen-15 and Other Techniques. *Journal of Environmental Quality*, *33*(2), 719–727. https://doi.org/10.2134/jeq2004.7190

Ortiz, C., Bosch, A.D., & Boixadera, J. (2005). Nitrogen pig slurry effects in a dry land cereal system. In: Proceedings of the 14th N Workshop, 24-26 October 2005, Maastricht, The Netherlands, 157–159

Parera, J., Domingo, F., Mallol, C., & Canut, N. (2010). Adaptación del uso de la conductividad eléctrica (CE) para determinar de forma rápida el contenido en nutrientes del purín de porcino en Catalunya. In: Libro de Actas II Congreso Español de Gestión Integral de Deyecciones Ganaderas, Barcelona, Spain. 9–10 June 2010, 67-76. ISBN: 978-84-936421-2-9

Paul, J. W., & Beauchamp, E. G. (1993). Nitrogen availability for corn in soils amended with urea, cattle slurry, and solid and composted manures. *Canadian Journal of Soil Science*, *73*(2), 253–266. https://doi.org/10.4141/cjss93-027

Pedersen, B. N., Christensen, B. T., Bechini, L., Cavalli, D., Eriksen, J., & Sørensen, P. (2020). Nitrogen fertilizer value of animal slurries with different proportions of liquid and solid fractions: A 3-year study under field conditions. *The Journal of Agricultural Science*, *158*(8–9), 707–717. https://doi.org/10.1017/S0021859621000083

Powell, J. M., Kelling, K. A., Muñoz, G. R., & Cusick, P. R. (2005). Evaluation of dairy manure nitrogen-15 enrichment methods on short-term crop and soil nitrogen budgets. *Agronomy Journal*, *97*(1), 333–337. https://doi.org/10.2134/agronj2005.0333

Pratt P.F., Broadbent, F.E., & Martin, J.P. (1973). Using, organic wastes as, organic fertilizers. *California Agriculture 27*, 10–13

SAS (2002). Statistical Analysis Software for Windows 9. Cary, NC, USA: SAS Institute Inc.

Schroder, J.J. (2005) Manure as a Suitable Component of Precise Nitrogen Nutrition. Proceedings 574, International Fertiliser Society, York, 32 p

Schröder, J. J., Jansen, A. G., & Hilhorst, G. J. (2006). Long-term nitrogen supply from cattle slurry. *Soil Use and Management*, *21*(2), 196–204. https://doi.org/10.1111/j.1475-2743.2005.tb00125.x

Schröder, J. J., Uenk, D., & Hilhorst, G. J. (2007). Long-term nitrogen fertilizer replacement value of cattle manures applied to cut grassland. *Plant and Soil*, *299*(1–2), 83–99. https://doi.org/10.1007/s11104-007-9365-7

Shakoor, A., Bosch-Serra, À. D., Lidon, A., Ginestar, D., & Boixadera, J. (2022). Soil nitrogen dynamics in fallow periods in a rainfed semiarid Mediterranean system. *Pedosphere, 32*. https://doi.org/10.1016/j.pedsph.2022.06.051

SMC (2019). Servei Meteorològic de Catalunya. Climatologies comarcals: La Noguera 1971-2000, http://www.meteo.cat/wpweb/climatologia/el-clima-ahir/climatologia-comarcal/ Accessed 31/10/2022

Soil Survey Staff (2014). Keys to Soil Taxonomy. USDA-Natural Resources Conservation 556 Service, Washington D.C

Sørensen, P. (2004). Immobilisation, remineralisation and residual effects in subsequent crops of dairy cattle slurry nitrogen compared to mineral fertiliser nitrogen. *Plant and Soil*, *267*(1–2), 285–296. https://doi.org/10.1007/s11104-005-0121-6

Sørensen, P., & Amato, M. (2002). Remineralisation and residual effects of N after application of pig slurry to soil. *European Journal of Agronomy*, *16*(2), 81–95. https://doi.org/10.1016/S11

Sørensen, P., & Thomsen, I. K. (2005). Separation of Pig Slurry and Plant Utilization and Loss of Nitrogen-15-labeled Slurry Nitrogen. *Soil Science Society of America Journal*, *69*(5), 1644–1651. https://doi.org/10.2136/sssaj2004.0365

Umbreit, W. W., & Bond, V. S. (1936). Analysis of Plant Tissue. *Industrial & Engineering Chemistry Analytical Edition*, *8*(4), 276–278. https://doi.org/10.1021/ac50102a018

Webb, J., Sorensen, P., Velthof, G. L., Amon, B., Pinto, M., Rodhe, L., Salomon, E., Hutchings, N., Burczyk, J., & Reid, J. E. (2011). Study on variation of manure N efficiency throughout Europe. (Final report). AEA Technology plc. http://ec.europa.eu/environment/water/water-nitrates/pdf/Man_N_Eff_Final%20Report.pdf Accessed 21/01/2015

Yagüe, M. R., & Bosch-Serra, A. D. (2013). Slurry field management and ammonia emissions under Mediterranean conditions. *Soil Use and Management*, *29*(3), 397–400. https://doi.org/10.1111/sum.12061

Yagüe, M. R., & Quílez, D. (2010). Direct and residual response of wheat to swine slurry application method. *Nutrient Cycling in Agroecosystems*, *86*(1), 161–174. https://doi.org/10.1007/s10705-009-9280-9

Yagüe, M. R., & Quílez, D. (2013). Residual Effects of Fertilization with Pig Slurry: Double Cropping and Soil. *Agronomy Journal*, *105*(1), 70–78. https://doi.org/10.2134/agronj2012.0191

Capítol 4. Diversification of winter rotations in Mediterranean rainfed cropping systems

4.1 Introduction

The The Farm to Fork Strategy sets ambitious goals to transform the EU's food production system into a more sustainable one. Such transformation (2030 horizon) includes the reduction of nutrient losses by 50 % and the use of fertilizers by at least 20 %, while ensuring that there is no deterioration in soil fertility (COM, 2020). To achieve these goals, the European Commission works with member states to extend sustainable agricultural practices, especially in areas with intensive livestock farming, which is the case of some Spanish regions.
The EU establishes (COM, 2018) a new Common Agricultural Policy and addresses environmental requirements, in order to achieve the objectives of the Green Deal (COM, 2019). The new policy also includes the eco-schemes concept, which are voluntary and climate-environmental friendly measures.

In the European agricultural landscape, winter cereals, including wheat and barley, are the most important grain crops. However, low nutrient utilization (i.e., N) and poor yields pose a major productivity problem for the semiarid region of the continent (Savin *et al*., 2019). Rainfed Spanish agriculture represents 77 % of the total cultivated area, mainly devoted to wheat and barley distributed in 4.6 million hectares with yields about 2.7 and 2.4 Mg/ha, respectively (MAPA, 2020). In these areas, the amount of precipitation is the most important limiting factor for productivity (Lassaletta *et al*., 2021; Jiménez-de-Santiago *et al*., 2019; López-Bellido *et al*., 2000) which is also associated to a high annual variability (SMC, 2019). Apart from that, the availability of plant nutrients, particularly N, is a constraint as soil organic matter is usually low (Serra 2010; López-Bellido & López-Bellido, 2001; Yang *et al*., 2006). The N efficiency in winter cereals grown in such environments is usually lower than in temperate areas (Bosch-Serra, 2010). Diversification of crop rotations has shown considerable potential to adapt to low soil moisture conditions and poor nutrient availability, although response effects are mediated by crop type (McDaniel *et al*., 2014; Tiemann *et al*., 2015). Therefore, proper crop rotation cycles, including leguminous crops and fallow periods, should have to be adopted to increase productivity, but also to reach the objectives established by the EU strategy.

Leguminous crops, are of great importance in the sustainability of global agriculture because of their unique ability to fix atmospheric N and providing residual N to non-legume crops (Pandey *et al*., 2016). Besides, it is considered that the inclusion of legumes in winter cereals rotations of Mediterranean areas can stabilize cereal yields and productivity in a climatic change context (Marini *et al*., 2020). However, a reduction in legume cultivation is a trend in the EU during the last decades (Zander *et al*., 2016).

By the end of 2021, Spain published a first version of the enhanced conditionality and the eco-schemes (MAPA, 2021a; MAPA, 2021b) where crop rotation, leguminous crops and fallow periods play an important role. Two Good Agricultural and Environmental Conditions (GAEC numbers 7 and 8) and two eco-schemes (eco-scheme numbers 3 and 5) have been implemented as an evolution of the Greening requirements and the areas of ecological interest. The GAEC-7 and the eco-scheme-3 promote crop rotations, and GAEC-8 and eco-scheme-5 enhance the non-productive areas within the crop farm, such as fallow areas. Subsequently, these options will represent an opportunity for the Spanish agriculture to preserve soil potential and to increase the efficiency and availability of nutrients.

The use of N fertilizer in Mediterranean rainfed agriculture is an opportunistic practice that depends primarily on rainfall and the resulting availability of soil moisture (Martínez *et al.*, 2017). It is well known that the rates of the N fertilizers greatly affect the crop production in terms of grain yield, biomass yield, profitability and N uptake (Vetsch *et al*., 2019). However, in the Mediterranean countries, the erratic rainfall distribution constraints the selection of the optimum N rate. This peculiarity signals the introduction of fallow as an essential practice in Mediterranean countries.

On the other side, the use of crop rotations and their large benefits related to the improvement of nutrient availability (Ryan *et al.*, 2008; Shah *et al.*, 2017; Sieling & Kage 2010; Yau *et al.*, 2003), the enhancement of soil protection and its quality (Larkin & Honeycutt 2006), the reduction of pest and disease prevalence (Ahuja *et al.*, 2010; Kirkegaard & Sarwar 1998) or the minimization of weed infestation (Wezel *et al.*, 2014) are well known. Although crop rotation is widely recommended for improving agrosystems, not so many crops are suitable for semiarid conditions, which means that the right choose of the break-crop in a rotation period is relevant to maintain yields. The introduction of legume crops like peas, clover, or soybean in a winter cereal rotation can significantly reduce N fertilizer requirements and increase crop yields (Papastylianou, 2004; Al-Ajlouni *et al.*, 2010; Buddenhagen, 1990; St. Luce *et al.*, 2015). The rotation of winter cereal (wheat) and legume (peas) also increases N use efficiency of both crops (Ooro *et al.*, 2021). In addition, the introduction of rapeseed in a winter cereal rotation also increases grain yield (Sieling & Christen, 2015) and the N balance in both crops can be also enhanced when PS is used as fertilizer (Sieling & Kage, 2006).

Nevertheless, the benefits of the introduction of leguminous and cruciferous crops in a winter cereal rotation, combined with fallow periods, and with the use of organic amendments, are still unclear under semiarid Mediterranean conditions due to the erratic rainfall. We hypothesize that the crop sequence, the features of the break crop and the type of fertilizer used in a crop rotation after a fallow period will influence the global results in a rotation cycle. Keeping all these points in mind, the main objective of this research work was to evaluate different fertilization strategies (with mineral fertilizers or PS), in the framework of two rotations which include two crops: winter barley (after or before) rapeseed or peas (Fig. 4.1) and fallow seasons.

Fig. 4.1 Detail of the field experiment with (a) the barley and rapeseed plots at their first stages, by the end of winter, in the 2014-15 cropping season and (b) the barley and peas (light green colored bands) plots at the spring of the 2019-20 cropping season.

4.2 Materials and methods

4.2.1 Study site, soil and climatic conditions

This research work belongs to a long-term experiment that started in 2002. The experimental field was located in Oliola (41º 52’30” N, 1º 09’10” E; 416 m a.s.l.), Lleida, Spain (Fig. 4.1). The soil is described as Typic Xerofluvent (Soil Survey Staff, 2014) having a silty loam texture. It is calcareous and non-saline with an electrical conductivity (EC, 1:5; soil: distilled water) of 0.18 dS/m. The average soil pH (1:2.5; soil: distilled water) was 8.2. The organic matter content was 15 g/kg for the 0-30 cm depth.

The climate in the area is classified as semiarid Mediterranean. Daily meteorological data is available from an automatic meteorological station next to the experimental field. The average annual precipitation between 2014 and 2020 was 455 mm, ranging from 348 mm in 2015 to 662 mm in 2018, with a high average reference crop anual evapotranspiration of 1079 mm, obtained from the Penman-Monteith equation (Allen *et al.*, 1998).

4.2.2 Experimental design and treatments

After the 2013-14 fallow season, barley (*Hordeum vulgare* L.)-rapeseed (*Brassica napus* L.) and rapeseed-barley rotations were introduced in 2014-15 and 2015-16. The 2016-17 season was left under fallow, and in the 2017-18 period a wheat crop (*Triticum aestivum* L.) was established but no fertilizers were applied. Barley-peas (*Pisum sativum* L.) and peas-barley rotations were established in 2018-19 and 2019-20 cropping seasons. Rapeseed was sown the 18th and 22nd September in 2014 and 2015, respectively. Barley was sown the 9th, the 10th, the 13th and the 4th November, in 2014, 2015, 2018 and 2019, respectively. Peas were sown the 13th and the 4th November in 2018 and 2019, respectively. In 2014-15 and 2015-16, barley and rapeseed were harvested the 12th June and the 20th June, respectively. In 2018-19 and 2019-20, barley and peas were harvested the 6th July and the 17th June, respectively.

Mineral fertilizer and PS were used as N sources. Nitrogen application rates applied at sowing (2) and at topdressing (9) during the experimental period are shown in Tab. 4.1. All N treatments at sowing (September) or at topdressing (February) were randomized against the block ant three blocks (repetitions) were established. Ammonium nitrate was used as a mineral N fertilizer. The mineral N treatments were 0N0, 0N1, 0N2 with no-N applied at sowing and 0, 60 and 120 kg N/ha applied in February. Additionally, doses of phosphorus (P) and potassium (K) were applied at seeding at 96.5 kg P_2O_5/ha and 107.2 kg K_2O/ha. Pig slurry was obtained from a nearby farm next to the field site. Slurries were sampled from each tank before field application and refrigerated for further analysis. In peas, mineral N treatments (0N0, 0N1 and 0N2) were maintained, but no slurries were applied. However, the 0N3 and 0N6 treatments (Tab. 4.1) received the same P and K rates that mineral N treatments in order to avoid P and K deficiencies.

Tab. 4.1 Average of Nitrogen application doses at sowing (Nsow) and the further amount of N applied at topdressing (Ntop) during the two rotation cycles of two concurrent cropping seasons each: Barley-rapeseed / Rapeseed-barley (2014-16) or Barley-peas / Peas-barley (2018-20).

Cropping seasons	**2014-15 / 2015-16**		**2018-19 / 2019-20**	
Crops	**Barley**	**Rapeseed**	**Barley**	**Peas**
Nsow treatment (Fertilizer origin)	N applied (kg N/ha)			
0N (Control)	0 / 0	0 / 0	0 / 0	0 / 0
PN (Fattening pig slurry)	169 / 155	162 / 331	109 / 84	0 / 0
Ntop treatment (Fertilizer origin)	N applied (kg N/ha)			
0 (Control)	0 / 0	0/0	0 / 0	0 / 0
1 (Mineral, ammonium nitrate)	60 / 60	60 / 60	60 / 60	60 / 60
2 (Mineral, ammonium nitrate)	120 / 120	120 / 120	120 / 120	120 / 120
3 (Fattening pig slurry)	143 / 169	143 / 169	115 / 143	0 / 0
4 (Fattening pig slurry)	219 / 265	219 / 265	231 / 285	0 / 0
5 (Fattening pig slurry)	357 / 506	357 / 506	417 / 471	0 / 0
6 (Sow slurry)	93 / 87	93 / 87	63 / 81	0 / 0
7 (Sow slurry)	190 / 177	190 / 177	125 / 162	0 / 0
8 (Sow slurry)	294 / 253	294 / 253	193 / 241	0 / 0

In the first rotation cycle, slurries were applied to rapeseed the 10th September 2014, the 10th February, the 21st September in 2015 and the 2nd February in 2016; in barley, they were applied the 23th October in 2014, the 10th February and 20th October in 2015 and the 2nd February in the 2016. In the second rotation cycle, slurries were applied to barley the 30th October in 2018, the 15th March, the 31st October in 2019 and the 10th February in 2020.

4.2.3 Soil and crop sampling and analysis

At the start of each cropping season or fallow period (September 2014 and 2015; October 2016, 2018, 2019 and December 2017), soil mineral N was analyzed in 0N0, 0N2 and 0N5 treatments (Tab. 4.1) and associated crops. A composite soil sample was obtained from two points in each plot, from 0–90 cm depth at intervals of 0–30 cm each. An Edelman auger (7 cm diameter) was used. Composite samples came from each of three replicates of both treatments. The soil mineral N content was measured by extracting 20±0.5 g of soil with 50 mL of 1M potassium chloride. These soil extracts were examined with a continuous flow auto-analyzer (Seal Analytical, SealAutoanalyzer3, Norderstedt, Germany). Results were transformed to kg N/ha units, on a dry soil basis, taking into account the averaged bulk density for each depth and its soil moisture. The gravimetric soil moisture was determined in a subsample by oven-drying at 105 ºC until constant weight.

For the determination of total biomass, crop yield and N-uptake, plant samples were annually taken at the time of harvesting. For each rotation cycle, a mower was used to harvest the crops from a 12 m^2 area. The total fresh crop yield was obtained directly on the field during harvest. One crop subsample per plot was taken and stored at 4°C for a maximum of 48 hours before being analyzed for dry matter and N content. The dry matter was obtained by drying at 60 °C, and the N content was determined by Kjeldahl digestion, but a NIR spectroscopic process was used for grain barley.

4.2.4 Statistical analysis

The data was statistically analyzed by using the statistical package SAS (v9.4). The SAS System's MIXED procedure (Littell *et al.*, 1996) was used for all analyses of crop yield, N-uptake and biomass variables. We chose to use AIC (Akaike, 1974) to compare the relative goodness-of-fit among non-nested candidate models. The performance of AIC was better when N at sowing, N at topdressing, rotation cycle interaction effects were considered fixed and block and block triple interaction were considered random. We tested for homogeneity of variances and normality of distributions. Only biomass was not normally distributed and were subjected to a log(log10) transformation and retested for normality. Multiple comparisons of least squares means of the main effects and interaction were made with the LSMEANS option. We selected a value of 5 % (i.e., $p < 0.05$) as the minimum criterion for significance.

4.3 Results

In the 2014-15, 2015-16, 2018-19 and 2019-20 cropping seasons and from October to June the amount of rainfall was increasing: 251, 290, 359, 590 mm, respectively. However, during the period from March to April, which coincides with the crop flowering stage, the amount of rainfall in 2014-15 (40 mm) and 2018-19 (45 mm) was much lower (drought period) than in 2015-16 (113 mm) and 2019-20 (170 mm) cropping seasons.

The available mineral N at the start of each cropping season varied with time and between the three studied treatments (control, 0N0; mineral, 0N2; slurry, 0N5; Tab. 4.1). In September 2014, it ranged from 250 (control) up to 559 kg N/ha (slurry). In September 2015, the control had 119 kg N/ha, while the mineral and slurry treatments attained 270 and 341 kg N/ha, respectively. During the 2017-18 cropping season the barley crop was not fertilized as the residual N in December 2017 ranged from 298 (control) up to 618 kg N/ha (slurry). The N availability averaged 123 kg N/ha in October 2018 (85-202 kg N/ha range). In October 2019 differences increased, from 230 kg N/ha in the control to 328 kg N/ha in the mineral; no data was available for slurry fertilized plots.

4.3.1 Total biomass

Total biomass was influenced by the sequence of the two crops in the 2014-16 rotation cycle (Tab. 4.2). The barley-rapeseed sequence produced more total biomass (21.72 Mg/ha) than the rapeseed-barley (18.16 Mg/ha) one (Tab. 4.2). In the second rotation cycle (2018-20) the total biomass for barley-peas (14.21 Mg/ha) was similar to the peas-barley one (13.57 Mg/ha) (Tab. 4.3).

Furthermore, there was no need to use N before planting to increase total biomass of both crops, but the N topdressing treatments led to significant differences (Tab. 4.2, Tab. 4.3). In the first rotation cycle (2014-16), annual N topdressing applications higher than 200 kg N/ha produced maximum total biomass (21-23 kg/ha) (Tab. 4.2). In the second rotation cycle (2018-20), the biennial N topdressing application higher than 400 kg N/ha level produced maximum total biomass (17.31 Mg/ha) (Tab. 4.3).

Tab. 4.2 Total biomass^{a} *(Mg/ha ± standard deviation) for each crop sequence (barley followed by rapeseed or in inverted order, but concurrent in time) in the first rotation cycle (2014-16), and according to fertilizer N treatments at sowing (Nsow) combined with the topdressing ones (Ntop)*^{b}*. Marginal means (MM) for the crop sequence in the rotation and treatments are also included.*

Rotation	Treatments	kg N/ha (Nsow)[c]			Treatments (in brackets) and MM for Ntop (2014-16)[d]
Barley-Rapeseed (2014-16)	kg N/ha (Ntop)	0-0 (0N)	169-162 (PN)	MM for Ntop	
	0 (0)	21.18 ± 1.60	22.44 ± 3.65	21.80 ± 0.63	(0) 18.37 ± 1.48 d
	60 (1)	17.17 ± 7.09	24.16 ± 2.12	20.66 ± 3.49	(1) 19.04 ± 4.32 c
MM for rotation	93 (6)	18.72 ± 0.87	22.68 ± 1.04	20.69 ± 1.98	(6) 19.06 ± 2.52 c
21.72 ± 1.78 A	120 (2)	19.71 ± 6.40	20.87 ± 1.02	20.28 ± 0.57	(2) 18.57 ± 0.60 d
	143 (3)	20.11 ± 2.74	21.66 ± 0.84	20.88 ± 0.72	(3) 19.99 ± 2.06 b
	190 (7)	20.77 ± 2.17	18.87 ± 1.73	19.81 ± 0.95	(7) 19.42 ± 1.75 b
	219 (4)	22.94 ± 6.51	29.09 ± 9.01	26.01 ± 3.07	(4) 22.94 ± 1.60 a
	294 (8)	18.80 ± 3.06	24.69 ± 5.02	21.74 ± 2.94	(8) 21.47 ± 1.60 a
	357 (5)	25.19 ± 4.42	21.99 ± 0.63	23.58 ± 1.59	(5) 21.41 ± 1.07 a
	MM for Nsow	20.51 ± 2.29	22.93 ± 2.66		SED_{Ntop}/LSD_{Ntop}: 0.03/ 0.02
Rapeseed-Barley (2014-16)	kg N/ha (Ntop)	0-0 (0N)	155-331 (PN)	MM for Ntop	
	0 (0)	12.61 ± 3.58	17.30 ± 0.84	14.95 ± 2.34	
	60 (1)	15.77 ± 1.18	19.10 ± 1.54	17.43 ± 1.66	
MM for rotation	87 (6)	19.20 ± 1.33	19.74 ± 0.80	19.47 ± 0.27	
18.16 ± 1.37 B	120 (2)	14.37 ± 2.16	20.50 ± 1.27	17.44 ± 3.06	
	169 (3)	16.22 ± 3.99	17.51 ± 1.26	16.87 ± 0.64	
	177 (7)	19.72 ± 2.42	20.02 ± 1.90	19.87 ± 0.14	
	253 (8)	19.52 ± 1.03	18.98 ± 1.91	19.25 ± 0.56	
	265 (4)	15.69 ± 0.23	22.52 ± 3.45	19.10 ± 3.41	
$SED_{rotation}$: 0.03	506 (5)	18.48 ± 1.10	19.61 ± 0.45	19.04 ± 0.56	
$LSD_{rotation}$: 0.02	MM for Nsow	16.84 ± 1.89	19.47 ± 1.49		

[a] Means followed by the different letter are significantly different according to the Least Significant Difference (LSD) for $p \leq 0.05$: capital letters A and B are used for differences between crop sequences and lower case letters for differences between Ntop treatments. The standard error of the difference (SED) is also shown. No significant differences were found for Nsow. No interactions were found between Nsow and Ntop treatments or with crop sequence.

[b] Numbers in brackets are the identification number for Ntop treatment (the same for both crops in a rotation) and according to Tab. 4.1.

[c] First number is the amount of N applied in barley, and the second number is the amount of N applied to rapeseed.

[d] The amount of N applied in each treatment is the average of both crop sequences and associated to the same treatment number (in brackets).

Tab. 4.3 Total biomass[a] (Mg/ha ± standard deviation) for each crop sequence (barley followed by peas or in inverted order, but concurrent in time) in the second rotation cycle (2018-20), and according to fertilizer N treatments at sowing (Nsow) combined with the topdressing ones (Ntop)[b]. Marginal means (MM) for the crop sequence in the rotation and treatments are also included.

Rotation	Treatments	kg N/ha (Nsow) [c]			Treatments (in brackets) and MM for Ntop (2018-20)[d]
Barley-Peas (2018-20)	kg N/ha (Ntop)	0-0 (0N)	109-0 (PN)	MM for Ntop	
	0-0 (0)	11.94 ± 2.11	14.94 ± 3.04	13.21 ± 2.44	(0) 12.26 ± 2.75 d
	60-60 (1)	12.71 ± 0.65	14.74 ± 1.88	13.72 ± 1.43	(1) 13.74 ± 1.25 c
MM for rotation	63-0 (6)	10.55 ± 3.34	13.00 ± 2.34	11.78 ± 1.74	(6) 11.38 ± 2.07 e
14.21 ± 1.13	115-0 (3)	12.36 ± 1.15	14.81 ± 3.10	13.59 ± 1.73	(3) 13.40 ± 2.54 c
	120-120 (2)	14.97 ± 2.09	15.26 ± 1.53	15.12 ± 0.20	(2) 15.44 ± 1.96 b
	125-0 (7)	13.34 ± 3.44	14.59 ± 1.77	13.97 ± 0.89	(7) 12.54 ± 2.24 d
	193-0 (8)	15.56 ± 2.36	16.27 ± 1.83	15.91 ± 0.50	(8) 14.54 ± 0.97 bc
	231-0 (4)	13.78 ± 1.05	15.53 ± 2.01	14.66 ± 1.24	(4) 14.59 ± 1.17 bc
	417-0 (5)	16.37 ± 1.70	16.34 ± 1.52	16.35 ± 0.03	(5) 17.31 ± 0.02 a
	MM for Nsow	13.46 ± 1.80	15.05 ± 0.94		SED_{Ntop}/LSD_{Ntop}: 0.02/ 0.02
Peas-Barley (2018-20)	kg N/ha (Ntop)	0-0 (0N)	84-0 (PN)	MM for Ntop	
	0-0 (0)	9.14 ± 0.74	13.49 ± 2.20	11.32 ± 3.07	
	60-60 (1)	13.00 ± 2.23	14.53 ± 3.20	13.77 ± 1.08	
	81-0 (6)	9.28 ± 1.68	12.69 ± 2.66	10.99 ± 2.41	
MM for rotation	120-120 (2)	13.13 ± 1.97	18.40 ± 1.87	15.76 ± 3.72	
13.57 ± 1.95	143-0 (3)	10.84 ± 1.15	15.60 ± 2.76	13.22 ± 3.36	
	162-0 (7)	10.15 ± 3.41	12.07 ± 2.00	11.11 ± 1.35	
	241-0 (8)	12.15 ± 1.33	14.19 ± 2.45	13.17 ± 1.44	
	285-0 (4)	13.75 ± 0.91	15.32 ± 1.35	14.53 ± 1.11	
	471-0 (5)	18.30 ± 3.54	18.28 ± 0.91	18.29 ± 0.01	
	MM for Nsow	12.19 ± 2.68	14.95 ± 2.10		

[a] Means followed by the different letter are significantly different according to the Least Significant Difference (LSD) for $p \leq 0.05$. The standard error of the differences (SED) are also shown. No interactions were found between N_{sow} and N_{top} treatments or with crop sequence in the rotation.

[b] Numbers in brackets are the identification number for Ntop treatment according to Tab. 4.1. First number is the amount of N applied in barley, second number is the amount of N applied (only from mineral origin) to peas.

[c] First number is the amount of N (from slurry origin) applied in barley, and the second number is the amount of N applied to peas at sowing.

[d] The amount of N applied in each treatment is the average of both crop sequences and associated to the same treatment number (in brackets).

4.3.2 Total N uptake

In the different rotations of two crops (Tab. 4.4, Tab. 4.5), the highest N uptake occurred when barley was first introduced within the sequence (349 and 253 kg N/ha, in the first and second rotation, respectively). Differences were around 70 or 60 kg N/ha compared when barley was introduced at the second crop. Whatever the rotation, fertilization at sowing increased N uptake.

The total N uptake was also influenced by the application of N at topdressing in both crop rotation cycles. In the barley-rapeseed rotation (Tab. 4.4), the highest N uptake (392 kg N/ha) was achieved by the highest dose of this nutrient (average rate of 431 kg N/ha). It is interesting to underline the N uptake (257 kg N/ha) when no N was applied. In the second rotation (2018-20; barley and peas), these effects varied according to the previous crop history, as shown by the significant rotation and N at topdressing interaction (Tab. 4.5), but also to the fact that no PS were applied on peas, thus, expressing N residual effects. In both rotations (2018-19 and 2019-20), the mineral treatments and the highest doses of slurries at topdressing achieved the most important N uptakes.

Tab. 4.4 Total Nitrogen uptake[a] *(kg/ha, ± standard deviation) for each crop sequence (barley followed by rapeseed or in inverted order, but concurrent in time) in a rotation cycle (2014-16), and according to fertilizer treatments at sowing (Nsow) combined with the topdressing ones (Ntop)* [b]*. Marginal means (MM) for the crop sequence in the rotation and fertilizer treatments are also included.*

Rotation	Treatments	kg N/ha (Nsow) [c]			Treatments (in brackets) and MM for Ntop (2014-16)[d]
Barley-Rapeseed (2014-16)	kg N/ha (Ntop)	0-0 (0N)	169-162 (PN)	MM for Ntop	
	0 (0)	288.4 ± 24.5	352.1 ± 34.2	320.2 ± 28.3	(0) 257.1 ± 31.2 d
	60 (1)	229.4 ± 9.54	413.0 ± 19.5	321.2 ± 14.5	(1) 290.1 ± 30.5 c
	93 (6)	237.9 ± 18.3	357.5 ± 30.9	297.7 ± 24.6	(6) 260.3 ± 25.7 d
	120 (2)	345.0 ± 58.2	382.8 ± 40.4	363.9 ± 49.3	(2) 317.1 ± 55.1 b
MM for rotation	143 (3)	284.2 ± 44.4	372.8 ± 15.4	328.5 ± 29.9	(3) 295.6 ± 23.1 c
348.7 ± 52.2A	190 (7)	295.3 ± 41.8	331.5 ± 28.4	313.4 ± 35.1	(7) 293.3 ± 33.8 c
	219 (4)	319.1 ± 44.6	400.0 ± 26.9	359.5 ± 35.7	(4) 334.2 ± 42.0 b
	294 (8)	291.4 ± 34.4	492.6 ± 51.6	392.0 ± 43.0	(8) 348.7 ± 29.3 b
	357 (5)	437.5 ± 31.1	446.3 ± 16.2	441.9 ± 23.6	(5) 392.0 ± 23.7 a
	MM for Nsow	303.1 ± 66.7	394.3 ± 37.7		$\mathrm{SED_{Ntop}}$/$\mathrm{LSD_{Ntop}}$: 25.4/17.4
Rapeseed-Barley (2014-16)	kg N/ha (Ntop)	0-0 (0N)	155-331 (PN)	MM for Ntop	
	0 (0)	141.0 ± 43.0	247.2 ± 25.4	194.1 ± 34.2	
	60 (1)	217.1 ± 11.8	300.9 ± 81.4	259.0 ± 46.6	
	87 (6)	146.1 ± 39.6	299.9 ± 14.3	223.0 ± 26.9	
	120 (2)	253.4 ± 63.2	287.3 ± 58.9	270.3 ± 61.0	
MM for rotation	169 (3)	204.8 ± 19.4	320.9 ± 12.5	262.8 ± 16.4	
271.0 ± 37.9B	177 (7)	235.7 ± 18.5	310.8 ± 46.8	273.2 ± 32.6	
	265 (4)	289.4 ± 60.7	328.7 ± 35.9	309.0 ± 48.3	
	253 (8)	278.4 ± 51.1	332.6 ± 11.5	305.5 ± 31.3	
$\mathrm{SED_{rotation}}$: 18.9	506 (5)	329.9 ± 45.1	354.3 ± 42.6	342.1 ± 23.8	
$\mathrm{LSD_{rotation}}$: 13.2	MM for Nsow	232.9 ± 39.2	309.2 ± 36.6		
	MM for Nsow (2014-16)	268.0 ± 52.9y	351.7 ± 37.1x	$\mathrm{SED_{Ntop}}$/$\mathrm{LSD_{Ntop}}$: 17.5/12.4	

[a] Means followed by the different letter are significantly different according to the Least Significant Difference (LSD) for $p \leq 0.05$: capital letters (A and B) were used for differences between crop sequences, two lower case letters (x and y) for differences between Nsow treatments and the rest of lower case letters for differences between Ntop treatments. The standard error of the difference (SED) is also shown. No interactions were found.

[b] Numbers in brackets are the identification number for Ntop treatment (the same for both crops in a rotation) and according to Tab. 4.1.

[c] First number is the amount of N applied in barley, and the second number is the amount of N applied to rapeseed.

[d] The amount of N applied in each treatment is the average of both crop sequences and associated to the same treatment number (in brackets).

Tab. 4.5 Total Nitrogen uptake[a] *(kg/ha, ± standard deviation) for each crop sequence (barley followed by peas or in inverted order, but concurrent in time) in the second rotation cycle (2018-20), and according to fertilizer N treatments at sowing (Nsow) combined with the topdressing ones (Ntop)*[b]*. Marginal means (MM) for the crop sequence in the rotation and treatments are also included.*

Rotation	Treatments	kg N/ha (Nsow) [c]		
Barley-Peas (2018-20)	kg N/ha (Ntop)	0-0 (0N)	109-0 (PN)	MM for Ntop
	0-0 (0)	207.1 ± 27.0	256.9 ± 62.1	232.0 ± 44.5 c
	60-60 (1)	230.7 ± 12.2	276.2 ± 36.6	253.4 ± 24.4 cba
	63-0 (6)	178.1 ± 57.2	221.2 ± 11.9	199.7 ± 34.5 d
	115-0 (3)	220.6 ± 23.2	245.9 ± 71.9	233.2 ± 47.5 c
MM for rotation	120-120 (2)	283.1 ± 25.9	263.9 ± 31.2	273.5 ± 28.5 a
252.63 ± 11.5 A	125-0 (7)	238.4 ± 69.9	246.2 ± 21.0	242.3 ± 45.5 bc
	193-0 (8)	277.2 ± 45.6	279.4 ± 34.3	287.3 ± 39.9 a
	231-0 (4)	240.5 ± 12.8	292.3 ± 44.8	266.4 ±28.8 ba
	417-0 (5)	287.1 ± 16.9	282.8 ± 13.3	285.0 ± 15.1 a
	MM for Nsow	240.3 ± 32.2	262.8 ± 36.3	SED_{Ntop}/LSD_{Ntop}: 9.89/ 6.7
Peas-Barley (2018-20)	kg N/ha (Ntop)	0-0 (0N)	84-0 (PN)	MM for Ntop
	0-0 (0)	114.5 ± 21.2	179.1 ± 10.8	146.8 ± 15.9 c
	60-60 (1)	175.1 ± 26.6	214.2 ± 43.4	194.7 ± 34.9 b
	81-0 (6)	109.5 ± 15.9	180.0 ± 32.3	144.8 ± 24.1 c
	120-120 (2)	201.1 ± 35.4	293.6 ± 27.5	247.3 ± 31.5 a
MM for rotation	143-0 (3)	157.3 ± 6.7	229.9 ± 41.0	193.7 ± 23.8 b
192.5 ± 11.5 B	162-0 (7)	131.2 ± 43.8	164.6 ± 21.7	147.9 ± 32.7 c
	241-0 (8)	168.8 ± 27.0	205.6 ± 44.5	187.0 ± 35.7 b
	285-0 (4)	187.4 ± 17.6	215.0 ± 20.1	201.2 ± 18.9 b
$\text{SED}_{\text{rotation}}$: 14.0	471-0 (5)	240.5 ± 35.2	303.9 ± 34.9	272.2 ± 35.0 a
$\text{LSD}_{\text{rotation}}$: 11.3	MM for Nsow	165.1± 25.5	220.7 ± 30.7	SED_{Ntop}/LSD_{Ntop}: 11.1/ 7.6
	MM for Nsow (2018-20)	202.7 ± 10.9 y	241.7 ± 10.8 x	SED_{Ntop}/LSD_{Ntop}: 11.5/ 8.5

[a] An interaction was found between crop sequence in the rotation and Ntop. Means followed by the different letter are significantly different according to the Least Significant Difference (LSD) for $p \leq 0.05$: capital letters (A and B) were used for differences between crop sequences, two lower case letters (x and y) between Nsow treatments and the rest of lower case letters for differences between Ntop treatments. The standard error of the differences (SED) are also shown.

[b] Numbers in brackets are the identification number for Ntop treatment according to Tab. 4.1. First number is the amount of N applied in barley, and the second number is the amount of mineral N applied to peas.

[c] First number is the amount of N applied in barley, second number is the amount of N applied to peas.

4.3.3 Crop yields

The average crop yields for barley were 4.21, 5.51, 4.29 and 4.02 Mg/ha for the 2014-15, 2015-16, 2018-19 and 2019-20 seasons, respectively (Tab. 4.6, Tab. 4.7). Rapeseed yields averaged 2.51 and 3.12 Mg/ha in 2014-15 and 2015-16, respectively (Tab. 4.6). Peas yields averaged 2.13 and 3.94 Mg/ha in 2018-19 and 2019-20 seasons (Tab. 4.7). Fertilization at sowing enhanced yields except in the 2014-15 cropping season (Tab. 4.6, Tab. 4.7).

The interaction of crop and N at topdressing was significant. Rapeseed yield gave no-productive answer to N topdressing. However, in barley and in 2014-15 season, mineral treatments yielded the lowest, but in the second year (2015-16), only the control gave the lowest barley yields, without differences between the rest of the treatments (Tab. 4.6). In 2018-19, the highest barley yields were achieved in the 193 and 417 kg N ha^{-1} application. In 2019-20 the best yields were attained under the highest mineral N fertilization (120 kg N/ha) and in slurry rates between 285 and 471 kg N/ha (Tab. 4.7). Pea yields were maintained at highest interval with mineral N applications of 60 and 120 kg N/ha at topdressing in each cropping season (Tab. 4.7), although numbers doubled in 2019-20 (average of 4.3 Mg/ha) *vs*. 2018-19 (average of 2.3 Mg/ha)

Tab. 4.6 Crop yield biomass[a] *(Mg/ha ± standard deviation) for barley and rapeseed in each cropping season of the rotation cycle (2014-16) and according to fertilizer treatments at topdressing (Ntop)*[b] *as a significant interaction between the two variables was found. No interaction was found between crops and fertilization at sowing (Nsow)*[c]*. Marginal means (MM) for the crops and Nsow for each year are also included.*

2014-15	kg N/ha (Ntop)									kg N/ha (Nsow)	
Crop	0 (0)	60 (1)	93 (6)	120 (2)	143 (3)	190 (7)	219 (4)	294 (8)	357 (5)	0-0 (0N)	169-162 (PN)
Barley MM_{crop}: 4.21± 0.50	4.56± 0.34a	3.84 ± 0.65bc	4.29 ± 0.20a	3.54 ± 0.39c	4.37 ± 0.35a	4.25 ± 0.39ab	4.15 ± 0.47ab	4.30 ± 0.47a	4.55 ± 0.31a	4.20 ± 0.51	4.21 ± 0.05
	$SED_{crop*Ntop}$: 0.22 / $LSD_{crop*Ntop}$: 1.48										
Rapeseed MM_{crop}: 2.51±0.33	2.47 ± 0.30	2.76 ± 0.63	2.51 ± 0.34	2.37 ± 0.24	2.55 ± 0.19	2.63 ± 0.37	2.40 ± 0.52	2.65 ± 0.16	2.43 ± 0.22	2.51 ± 0.39	2.55 ± 0.27
										MM for Nsow: 3.37 ± 0.93	MM for Nsow: 3.38 ± 0.93

2015-16	kg N/ha (Ntop)									kg N/ha (Nsow)	
Crop	0 (0)	60 (1)	87 (6)	120 (2)	169 (3)	177 (7)	253 (8)	265 (4)	506 (5)	0-0 (0N)	155-331 (PN)
Rapeseed MM_{crop}: 3.12±0.67	2.97± 0.81	3.53 ± 0.64	2.82 ± 0.74	3.13 ± 0.72	3.03 ± 0.78	2.73 ± 0.20	3.16 ± 0.62	3.31 ± 0.63	3.50 ± 0.63	2.82 ± 0.67	3.41 ± 0.52
Barley MM_{crop}: 5.51± 1.04	4.52 ± 1.44b	4.96 ± 1.38ba	5.43 ± 1.30ba	5.41 ± 1.39ba	5.77 ± 0.69a	5.95 ± 0.49a	5.96 ± 0.53a	6.10± 0.34a	5.46 ± 0.57ba	5.11 ± 0.11	5.90 ± 0.88
	$SED_{crop*Ntop}$: 0.50 / $LSD_{crop*Ntop}$: 0.34									MM for Nsow: 3.99 ± 0.15 x	MM for Nsow: 4.67± 0.14 y
										SED_{Nsow}: 1.96 LSD_{Nsow}: 1.47	

---

[a] Means followed by the different letter are significantly different according to the Least Significant Difference (LSD): two lower case letters (x and y) were used for differences between Nsow treatments and the rest of lower case letters for differences between Ntop treatments for each crop. The standard error of the differences (SED) are also shown.

[b] Numbers in brackets are the identification number for Ntop treatments according to Tab. 4.1.

[c] First number is the amount of N applied in barley, and the second number is the amount of N applied to rapeseed.

Tab. 4.7 Crop yield biomass[a] (Mg/ha ± standard deviation) for barley and peas in each cropping season of the second rotation cycle (2018-20) and according to fertilizer treatments at topdressing (Ntop)[b] as a significant interaction between the two variables was found. No interaction was found between crops and fertilization at sowing (Nsow)[c]. Marginal means (MM) for each crop and Nsow for each year are also included.

2018-19	kg N/ha (Ntop)									kg N/ha (Nsow)	
Crop	0-0 (0)	60-60 (1)	63-0 (6)	115-0 (3)	120-120 (2)	125-0 (7)	193-0 (8)	231-0 (4)	417-0 (5)	0-0 (0N)	109-0 (PN)
Barley MM: 4.29 ± 0.99	3.50 ± 0.87de	4.19 ± 0.41cd	3.41 ± 0.80e	3.94 ± 0.70cde	4.49 ± 0.78bc	4.10 ± 0.47cde	5.08 ± 0.42ab	4.56 ± 0.49bc	5.35 ± 0.62a	3.84 ± 0.56	4.74 ± 0.67
	SED$_{crop*Ntop}$: 0.33 LSD$_{crop*Ntop}$: 0.23										
Peas MM: 2.13 ± 0.71	1.86 ± 0.68ab	2.18 ± 0.52ab	1.90 ± 0.60ab	2.43 ± 0.45a	2.39 ± 0.32a	1.64 ± 0.53b	2.06 ± 0.43ab	2.34 ± 0.71a	2.36 ± 0.59a	1.74 ± 0.52	2.51 ± 0.53
	SED$_{crop*Ntop}$: 0.33/ LSD$_{crop*Ntop}$: 0.23									MM for Nsow: 2.80 ± 1.34 y SED$_{Nsow}$: 0.19	MM for Nsow: 3.63 ± 1.32 x LSD$_{Nsow}$: 0.14

2019-20	kg N/ha (Ntop)									kg N/ha (Nsow)	
Crop	0-0 (0)	60-60 (1)	81-0 (6)	120-120 (2)	143-0 (3)	162-0 (7)	241-0 (8)	285-0 (4)	471-0 (5)	0-0 (0N)	84-0 (PN)
Peas MM: 3.94 ± 0.72	3.52 ± 0.44de	4.12 ± 0.32abc	3.28 ± 0.48e	4.52 ± 0.47a	3.72 ± 0.84cde	3.96 ± 0.85abcd	4.34 ± 1.01ab	4.09 ± 0.55abc	3.85 ± 0.55bcd	3.80 ± 0.54	4.07 ± 0.69
	SED$_{crop*Ntop}$: 0.40/ LSD$_{crop*Ntop}$: 0.27										
Barley MM: 4.02 ± 1.02	3.50 ± 0.97cd	3.98 ± 0.47bc	3.40 ± 0.98cd	4.46 ± 0.76ab	4.13 ± 1.02bc	3.00 ± 0.75d	3.78 ± 0.58bcd	4.53 ± 0.61ab	5.32 ± 0.45a	3.81 ± 0.66	4.21 ± 0.80
	SED$_{crop*Ntop}$: 0.40/ LSD$_{crop*Ntop}$: 0.27									MM for Nsow: 3.81 ± 0.89 y SED$_{Nsow}$: 0.12	MM for Nsow: 4.15 ± 0.84 x LSD$_{Nsow}$: 0.09

[a] Means followed by the different letter are significantly different according to the Least Significant Difference (LSD): two lower case letters (x and y) were used for differences between Nsow treatments and the rest of lower case letters for differences between Ntop treatments for each crop. The standard error of the differences (SED) is also shown.

[b] Numbers in brackets are the identification number for Ntop treatment according to Tab. 4.1. First number is the amount of N applied in barley, second number is the amount of N (mineral origin) applied to peas.

[c] First number is the amount of N (slurry origin) applied in barley, and the second number is the amount of N applied to peas at sowing.

4.4 Discussion

Yield results show the better adaptation of barley to spring drought periods than rapeseed and peas (Tab. 4.6, Tab. 4.7). In this study, the previous point led advantage to barley-rapeseed or barley-peas rotation over their inverse crop sequence. The spring climate conditions in the 2014-15 and in 2018-19 cropping seasons, where high temperatures and high ETo were combined with low precipitation, explained these results. In fact, barley has a much greater water use efficiency than rapeseed (Sadras & McDonald, 2011). Furthermore, peas yield is negatively influenced by drought and high temperatures (Dogan *et al.*, 2015, Xiao *et al.*, 2009). However, earlier drought periods at the end of winter, which coincides with cereal stem elongation development stage, might also negatively affect barley yields (Blum 1998). In the spring drought context of 2014-15, the high residual N after the fallow period (September 2014), which is a common pattern in these systems (Shakoor *et al.*, 2022), satisfied the N demand of barley and rapeseed at the highest recorded yields without N fertilization (Tab. 4.6). Besides, barley and rapeseed have an important root exploratory ability that enables them to reach water (Huang, 2000) and N at lower layers. In the spring drought context of 2018-19, with low residual N, barley needed >125 kg N/ha for maximum yields, while peas did not need additional N.

In the spring rainy context, rapeseed neither needed N fertilization in the 2015-16 cropping season (Tab. 4.6). As rapeseed absorbs relevant amounts of N at early stages (Villar *et al.*, 2019), this characteristic allowed taking profit of residual N in the soil. In fact, Porter *et al.*, (2020) found no rapeseed yield response to N soil supplies that exceeded 100 kg N/ha at six of seven studied sites. Thus, rapeseed introduction pointed out an interesting strategy to control the risk of nitrate leaching into underground water during the winter period and also to reduce the N inputs in the system. However, peas in the 2019-20 season (after barley) despite its ability to fix N from the atmosphere, needed a topdressing of 60 kg mineral-N/ha or its equivalent from residual N, which was associated to a preceding N topdressing slurry dose higher than 125 kg N/ha. Those results are supported by some authors (Achakzai & Bangulzai, 2006; Ejaz *et al.*, 2020), although the effect of soil residual N combined with the atmospheric N fixation (Wysokinski & Lozak, 2021) could also explain the significant response of peas to mineral-N topdressing (Tab. 4.7).

The different pattern of N absorption in barley, more important later in the cropping season (Carreck & Christian, 1991), led to barley yields to respond to N topdressing in a more abundant rainfall period (second year of each rotation). As water availability increased, additional N mineral supply, about 60 kg N/ha or around 90 kg N/ha from slurry origin, was needed (Tab. 4.6) in 2015-16, and a bit higher amount of 120 kg mineral-N/ha or around 162 kg slurry-N/ha in 2019-20. The slurry use at topdressing was in agreement with Bosch-Serra *et al.* (2015) in terms of the highest N use efficiency in winter barley monoculture.

Total biomass and N uptake in the barley-rapeseed rotation cycle increased according to N availability (Tab. 4.3, Tab. 4.4) and in agreement with Angás *et al.* (2006). Furthermore, slurries increased N uptake when compared with mineral fertilizers as Sieling *et al.* (2006) described. Total biomass production does not really concern to farmers. The excessive vegetative growth (because of excessive N supply) may cause early water depletion; thus, the lack of soil available water during grain filling and a yield reduction under Mediterranean conditions (Bosch-Serra 2010; Morell *et al.,* 2011; Tambussi *et al.*, 2007).

Biomass production and N uptake in the barley-peas rotation responded positively to N applied at topdressing, although the legume sequence inside a rotation was not significant (Tab. 4.3), despite being reasonable to expect it (Preissel *et al.,* 2015). Again, the low spring rainfall (2018-19) might benefit barley biomass.

It appears that the use of PS is a relatively reliable source of nutrients in Mediterranean semiarid areas, although its effectiveness will depend on climate and crop type. Drought periods are predicted to be more frequent in the Mediterranean region within a climate change scenario (Abd-Elmabod *et al.,* 2020; Marcos-García *et al.,* 2017), which might be aggravated by soil degradation (Ferreira *et al.,* 2022). Therefore, as barley seems to be the most suitable crop in such water stress conditions (*vs*. rapeseed or peas), if crop diversification must be successfully enhanced by the new Common Agricultural Policy, compensations for yield reductions should be included or maintained in the political guidelines.

Therefore, in semiarid areas with intensive livestock farming, the studied strategies should be considered a sound alternative to monoculture of barley, as the N balance becomes negative within the rotation cycle. It can be introduced as an additional option to other strategies proposed by other authors like the biennial or triennial application of organic amendments (Bosch-Serra *et al.,* 2015; Shepherd & Harrison, 2000), different crop rotations (Wezel *et al.*, 2014), or intercropping systems (Hauggaard-Nielsen *et al.*, 2007; Whitmore & Schröder, 2007; Zhang & Li, 2003). Understanding crop yields in semiarid environments, related to soil N and water dynamics, remains an important research area in long-term studies in order to fully justify the advantages of crop rotation diversification in rainfed agricultural systems.

4.5 Conclusions

Our study, based on several N fertilization strategies, provides empirical, field-based evidence for the suitability and constraints of growing barley combined with rapeseed or peas in Mediterranean rainfed agriculture. After a fallow period with a high residual mineral N in the soil rooting depth (> 250 kg N/ha), the crop sequence barley-rapeseed was the most suitable sequence in terms of total biomass and N uptake. Both crops took advantage of this residual N, and the highest yields were achieved without N. Nevertheless, potential yields of both crops were constrained by the March-April drought period, being rapeseed more affected than barley.

The introduction of a break-crop after fallow reduced by half the residual N, and the crop sequence barley-peas needed N fertilization to obtain the highest yields. The barley crop was again less affected by spring drought (*v*s. peas). Therefore, the barley-peas sequence resulted better than peas-barley, but required a minimum mineral N rate of 60 kg N/ha per year or a punctual slurry application of >125 kg N/ha on barley

As drought periods are difficult to predict, winter cereal monoculture shows the highest yield stability. The introduction of rapeseed is feasible in order to withdraw N. The inclusion of rapeseed and peas in the rotation also reduces the entrance of N in the system through fertilization. Both functions should be considered in order to reduce the N input in this agricultural systems and, as a consequence, to increase N use efficiency. However, EU policies might also compensate farmers for yield reduction if a more risky rotation will be promoted in semiarid environments in the context of better agricultural ecosystem services.

References

Abd-Elmabod, S. K., Muñoz-Rojas, M., Jordán, A., Anaya-Romero, M., Phillips, J. D., Jones, L., Zhang, Z., Pereira, P., Fleskens, L., van der Ploeg, M., & de la Rosa, D. (2020). Climate change impacts on agricultural suitability and yield reduction in a Mediterranean region. *Geoderma*, *374*, 114453. https://doi.org/10.1016/j.geoderma.2020.114453

Achakzai, A.K.K. & Bangulzai, M.I. (2006). Effect of various levels of nitrogen fertilizer on the yield and yield attributes of pea (Pisum sativum L.) cultivars. Pakistan Journal of Botany, 38(2),331–340. http://www.pakbs.org/pjbot/PDFs/38(2)/PJB38(2)331.pdf

Ahuja, I., Rohloff, J., & Bones, A. M. (2010). Defence mechanisms of Brassicaceae: implications for plant-insect interactions and potential for integrated pest management. A review. *Agronomy for Sustainable Development*, *30*(2), 311–348. https://doi.org/10.1051/agro/2009025

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control*, *19*(6), 716–723. https://doi.org/10.1109/TAC.1974.1100705

Al-Ajlouni, M.M., Al-Ghzawi, A.L.A. & Al-Tawaha, A.R. (2010). Crop rotation and fertilization effect on barley yield grown in arid conditions. Journal of Food, Agriculture & Environment,8 (3/4):869–872. ISSN: 1459-0255. https://eis.hu.edu.jo/deanshipfiles/pub106212880.pdf

Allen, R.G., Pereira, L.S., Raes, D. & Smith, M. (1998). Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrig Drain Pap 56. ISBN 92-5-104219-5. https://www.fao.org/3/x0490e/x0490e00.htm Accessed 30/06/2022

Angás, P., Lampurlanés, J., & Cantero-Martínez, C. (2006). Tillage and N fertilization. *Soil and Tillage Research*, *87*(1), 59–71. https://doi.org/10.1016/j.still.2005.02.036

Blum, A. (1998). Improving wheat grain filling under stress by stem reserve mobilisation. *Euphytica 1998 100:1*, *100*(1), 77–83. https://doi.org/10.1023/A:1018303922482

Bosch-Serra, A.D. (2010). Nitrogen use efficiency in rainfed Mediterranean agriculture. *Encyclopedia of Soil Science*, *1*(1), 1–6. Taylor and Francis. https://doi.org/10.1081/E-ESS-120044989

Bosch-Serra, A. D., Ortiz, C., Yagüe, M. R., & Boixadera, J. (2015). Strategies to optimize nitrogen efficiency when fertilizing with pig slurries in dryland agricultural systems. *European Journal of Agronomy 67*, 27–36. https://doi.org/10.1016/j.eja.2015.03.003

Buddenhagen, I. W. (1990). Legumes in Farming Systems in Mediterranean Climates. In *The Role of Legumes in the Farming Systems of the Mediterranean Areas* (pp. 3–29). Springer Netherlands. https://doi.org/10.1007/978-94-009-1019-5_1

Carreck, N. L., & Christian, D. G. (1991). Studies on the patterns of nitrogen uptake and translocation to the grain of winter barley intended for malting. *Annals of Applied Biology*, *119*(3)

COM (2018). Proposal for a regulation of the European Parliament and of the Council establishing rules on support for strategic plans to be drawn up by member states under the Common agricultural policy (CAP Strategic Plans) and financed by the European Agricultural Guarantee Fund (EAGF) and by the European Agricultural Fund for Rural Development (EAFRD) and repealing Regulation (EU) No 1305/2013 of the European Parliament and of the Council and Regulation (EU) No 1307/2013 of the European Parliament and of the Council. EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2018:392:FIN Accessed 30/06/2022

COM (2019). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: The European Green Deal. EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2019:640:FIN Accessed 30/06/2022

COM (2020). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system. EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0381 Accessed 30/06/2022

Dogan, E., Rat, I., Kahraman, A., & Ipek, I.S. (2015). Green pea response to deficit irrigation rates under semi-arid climatic conditions. *Bulgarian Journal of Agricultural Science, 21*(5), 1005–1011. http://www.agrojournal.org/21/05-13.pdf

Ejaz, S., Batool, S., Anjum, M. A., Naz, S., Qayyum, M. F., Naqqash, T., Shah, K. H., & Ali, S. (2020). Effects of inoculation of root-associative Azospirillum and Agrobacterium strains on growth, yield and quality of pea (*Pisum sativum L.*) grown under different nitrogen and phosphorus regimes. *Scientia Horticulturae*, *270,* 109401. https://doi.org/10.1016/j.scienta.2020.109401

Ferreira, C. S. S., Seifollahi-Aghmiuni, S., Destouni, G., Ghajarnia, N., & Kalantari, Z. (2022). Soil degradation in the European Mediterranean region: Processes, status and consequences. *Science of The Total Environment*, *805*, 150106. https://doi.org/10.1016/j.scitotenv.2021.150106

Hauggaard-Nielsen, H., Jørnsgaard, B., Kinane, J., & Jensen, E. S. (2008). Grain legume–cereal intercropping: The practical application of diversity, competition and facilitation in arable and organic cropping systems. *Renewable Agriculture and Food Systems*, *23*(1), 3–12. https://doi.org/10.1017/S1742170507002025

Huang, B. (2000). Role of root morphological and physiological characteristics in drought resistance of plants. In: Wilkinson, E. Plant-environment interactions. CRC Press, 39-64. https://doi.org/10.1201/9780824746568

Jiménez-de-Santiago, Lidón, & Bosch-Serra. (2019). Soil Water Dynamics in a Rainfed Mediterranean Agricultural System. *Water*, *11*(4), 799. https://doi.org/10.3390/w11040799

Kirkegaard, J. A., & Sarwar, M. (1998). Biofumigation potential of brassicas. *Plant and Soil 1998 201:1*, *201*(1), 71–89. https://doi.org/10.1023/A:1004364713152

Larkin, R. P., & Honeycutt, C. W. (2006). Effects of Different 3-Year Cropping Systems on Soil Microbial Communities and Rhizoctonia Diseases of Potato. *Phytopathology®*, *96*(1), 68–79. https://doi.org/10.1094/PHYTO-96-0068

Lassaletta, L., Sanz-Cobena, A., Aguilera, E., Quemada, M., Billen, G., Bondeau, A., Cayuela, M. L., Cramer, W., Eekhout, J. P. C., Garnier, J., Grizzetti, B., Intrigliolo, D. S., Ruiz Ramos, M., Romero, E., Vallejo, A., & Gimeno, B. S. (2021). Nitrogen dynamics in cropping systems under Mediterranean climate: a systemic analysis. *Environmental Research Letters*, *16*(7), 073002. https://doi.org/10.1088/1748-9326/ac002c

Littell, R.C., Milliken, G.A., Stroup, W.W., & Wolfinger, R.D. (1996). SAS system for mixed models. SAS Institute, Cary

López-Bellido, L., López-Bellido, R. J., Castillo, J. E., & López-Bellido, F. J. (2000). Effects of Tillage, Crop Rotation, and Nitrogen Fertilization on Wheat under Rainfed Mediterranean Conditions. *Agronomy Journal*, *92*(6), 1054–1063. https://doi.org/10.2134/agronj2000.9261054x

López-Bellido, R., & López-Bellido, L. (2001). Efficiency of nitrogen in wheat under Mediterranean conditions: effect of tillage, crop rotation and N fertilization. *Field Crops Research*, *71*(1), 31–46. https://doi.org/10.1016/S0378-4290(01)00146-0

MAPA (2020). Ministerio de Agricultura, Pesca y Alimentación. Anuario de estadística 2020. https://www.mapa.gob.es/es/estadistica/temas/publicaciones/anuario-de-estadistica/2020/default.aspx Accessed 12/11/2021.

MAPA (2021a). Ministerio de Agricultura, Pesca y Alimentación. Aplicación de la condicionalidad reforzada en el marco del plan estratégico de la PAC. https://www.mapa.gob.es/es/pac/post-2020/3-6-condicionalidad_tcm30-581377.pdf Accessed 12/11/2021.

MAPA (2021b). Ministerio de Agricultura, Pesca y Alimentación. El plan estratégico de la PAC de España (2023-2027). https://www.mapa.gob.es/es/pac/post-2020/el-pepac-de-espana-resumen-de-la-propuesta-dic-2021_tcm30-583992.pdf Accessed 12/11/2021.

Marcos-Garcia, P., Lopez-Nicolas, A., & Pulido-Velazquez, M. (2017). Combined use of relative drought indices to analyze climate change impact on meteorological and hydrological droughts in a Mediterranean basin. *Journal of Hydrology*, *554*, 292–305. https://doi.org/10.1016/j.jhydrol.2017.09.028

Marini, L., St-Martin, A., Vico, G., Baldoni, G., Berti, A., Blecharczyk, A., Malecka-Jankowiak, I., Morari, F., Sawinska, Z., & Bommarco, R. (2020). Crop rotations sustain cereal yields under a changing climate. *Environmental Research Letters*, *15*(12), 124011. https://doi.org/10.1088/1748-9326/abc651

Martínez, E., Maresma, A., Biau, A., Berenguer, P., Cela, S., Santiveri, F., Michelena, A., & Lloveras, J. (2017). Long-term effects of pig slurry combined with mineral nitrogen on maize in a Mediterranean irrigated environment. *Field Crops Research*, *214*, 341–349. https://doi.org/10.1016/j.fcr.2017.09.025

McDaniel, M. D., Tiemann, L. K., & Grandy, A. S. (2014). Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. *Ecological Applications*, *24*(3), 560–570. https://doi.org/10.1890/13-0616.1

Morell, F. J., Lampurlanés, J., Álvaro-Fuentes, J., & Cantero-Martínez, C. (2011). Yield and water use efficiency of barley in a semiarid Mediterranean agroecosystem: Long-term effects of tillage and N fertilization. *Soil and Tillage Research*, *117*, 76–84. https://doi.org/10.1016/j.still.2011.09.002

Ooro, P. A., Birech, R. J., Malinga, J. N., & Thuranira, E. (2021). Effect of Legumes on Nitrogen Use Efficiency of Wheat in a Short Term Crop Rotation in Njoro Sub-County. *Journal of Experimental Agriculture International*, 1–15. https://doi.org/10.9734/jeai/2021/v43i330652

Pandey, M. K., Roorkiwal, M., Singh, V. K., Ramalingam, A., Kudapa, H., Thudi, M., Chitikineni, A., Rathore, A., & Varshney, R. K. (2016). Emerging Genomic Tools for Legume Breeding: Current Status and Future Prospects. *Frontiers in Plant Science*, *7*. https://doi.org/10.3389/fpls.2016.00455

Papastylianou, I. (2004). Effect of rotation system and N fertilizer on barley and vetch grown in various crop combinations and cycle lengths. *The Journal of Agricultural Science*, *142*(1), 41–48

Porter, M. J., Pan, W. L., Schillinger, W. F., Madsen, I. J., Sowers, K. E., & Tao, H. (2020). Winter canola response to soil and fertilizer nitrogen in semiarid Mediterranean conditions. *Agronomy Journal*, *112*(2), 801–814. https://doi.org/10.1002/agj2.20119

Preissel, S., Reckling, M., Schläfke, N., & Zander, P. (2015). Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: A review. *Field Crops Research*, *175*, 64–79. https://doi.org/10.1016/j.fcr.2015.01.012

Ryan, J., Pala, M., Masri, S., Singh, M., & Harris, H. (2008). Rainfed wheat-based rotations under Mediterranean conditions: Crop sequences, nitrogen fertilization, and stubble grazing in relation to grain and straw quality. *European Journal of Agronomy*, *28*(2), 112–118. https://doi.org/10.1016/j.eja.2007.05.008

Sadras, V.O., & McDonald, G. (2011). Water use efficiency of grain crops in Australia: principles, benchmarks and management. Grains Research and Development Corporation, South Australian Research and Development Institute and University of Adelaide. https://grdc.com.au/__data/assets/pdf_file/0030/159186/grdcpublicationwateruseefficiencyofgraincropsinaustraliapdf.pdf.pdf ISBN: 978-1-921779-40-4

Savin, R., Sadras, V. O., & Slafer, G. A. (2019). Benchmarking nitrogen utilisation efficiency in wheat for Mediterranean and non-Mediterranean European regions. *Field Crops Research*, *241*, 107573. https://doi.org/10.1016/j.fcr.2019.107573

Shah, A., Askegaard, M., Rasmussen, I. A., Jimenez, E. M. C., & Olesen, J. E. (2017). Productivity of organic and conventional arable cropping systems in long-term experiments in Denmark. *European Journal of Agronomy*, *90*, 12–22. https://doi.org/10.1016/J.EJA.2017.07.001

Shakoor, A., Bosch-Serra, À. D., Lidon, A., Ginestar, D., & Boixadera, J. (2022). Soil nitrogen dynamics in fallow periods in a rainfed semiarid Mediterranean system. *Pedosphere*. https://doi.org/10.1016/j.pedsph.2022.06.051

Shepherd, M.A., & Harrison, R. (2000). Managing organic manures —is the closed nitrogen cycle achievable? *Aspects of Applied Biology 62*,119–124

Sieling, K., & Christen, O. (2015). Crop rotation effects on yield of oilseed rape, wheat and barley and residual effects on the subsequent wheat. *Archives of Agronomy and Soil Science*, 1–19. https://doi.org/10.1080/03650340.2015.1017569

Sieling, K., & Kage, H. (2006). N balance as an indicator of N leaching in an oilseed rape – winter wheat – winter barley rotation. *Agriculture, Ecosystems & Environment*, *115*(1–4), 261–269. https://doi.org/10.1016/j.agee.2006.01.011

Sieling, K., & Kage, H. (2010). Efficient N management using winter oilseed rape. A review. *Agronomy for Sustainable Development*, *30*(2), 271–279. https://doi.org/10.1051/agro/2009036

Sieling, K., Brase, T., & Svib, V. (2006). Residual effects of different N fertilizer treatments on growth, N uptake and yield of oilseed rape, wheat and barley. *European Journal of Agronomy*, *25*(1), 40–48. https://doi.org/10.1016/j.eja.2006.03.002

SMC (2019). Servei Meteorològic de Catalunya. Climatologies comarcals. Generalitat de Catalunya. https://www.meteo.cat/wpweb/climatologia/el-clima-ahir/climatologia-comarcal/ Accessed 31/10/2022.

Soil Survey Staff (2014). Keys to Soil Taxonomy. USDA-Natural Resources Conservation Service, Washington D.C

St. Luce, M., Grant, C. A., Zebarth, B. J., Ziadi, N., O'Donovan, J. T., Blackshaw, R. E., Harker, K. N., Johnson, E. N., Gan, Y., Lafond, G. P., May, W. E., Khakbazan, M., & Smith, E. G. (2015). Legumes can reduce economic optimum nitrogen rates and increase yields in a wheat–canola cropping sequence in western Canada. *Field Crops Research*, *179*, 12–25. https://doi.org/10.1016/j.fcr.2015.04.003

Tambussi, E. A., Bort, J., & Araus, J. L. (2007). Water use efficiency in C 3 cereals under Mediterranean conditions: a review of physiological aspects. *Annals of Applied Biology*, *150*(3), 307–321. https://doi.org/10.1111/j.1744-7348.2007.00143.x

Tiemann, L. K., Grandy, A. S., Atkinson, E. E., Marin-Spiotta, E., & McDaniel, M. D. (2015). Crop rotational diversity enhances belowground communities and functions in an agroecosystem. *Ecology Letters*, *18*(8), 761–771. https://doi.org/10.1111/ele.12453

Vetsch, J. A., Randall, G. W., & Fernández, F. G. (2019). Nitrate Loss in Subsurface Drainage from a Corn–Soybean Rotation as Affected by Nitrogen Rate and Nitrapyrin. *Journal of Environmental Quality*, *48*(4), 988–994. https://doi.org/10.2134/jeq2018.11.0415

Villar, N., Aranguren, M., Castellón, A., Besga, G., & Aizpurua, A. (2019). Soil nitrogen dynamics during an oilseed rape (Brassica napus L.) growing cycle in a humid

Mediterranean climate. *Scientific Reports*, *9*(1), 13864. https://doi.org/10.1038/s41598-019-50347-1

Wezel, A., Casagrande, M., Celette, F., Vian, J.-F., Ferrer, A., & Peigné, J. (2014). Agroecological practices for sustainable agriculture. A review. *Agronomy for Sustainable Development*, *34*(1), 1–20. https://doi.org/10.1007/s13593-013-0180-7

Whitmore, A. P., & Schröder, J. J. (2007). Intercropping reduces nitrate leaching from under field crops without loss of yield: A modelling study. *European Journal of Agronomy*, *27*(1), 81–88. https://doi.org/10.1016/j.eja.2007.02.004

Wysokinski, A., & Lozak, I. (2021). The Dynamic of Nitrogen Uptake from Different Sources by Pea (Pisum sativum L.). *Agriculture*, *11*(1), 81. https://doi.org/10.3390/agriculture11010081

Xiao, G., Zhang, Q., Wang, R., Yao, Y., Zhao, H., Bai, H., & Xiong, Y. (2009). Effects of Temperature Increase on Pea Production in a Semiarid Region of China. *Air, Soil and Water Research*, *2*, ASWR.S2488. https://doi.org/10.4137/ASWR.S2488

Yang, S.-M., Malhi, S. S., Song, J.-R., Xiong, Y.-C., Yue, W.-Y., Lu, L. L., Wang, J.-G., & Guo, T.-W. (2006). Crop yield, nitrogen uptake and nitrate-nitrogen accumulation in soil as affected by 23 annual applications of fertilizer and manure in the rainfed region of Northwestern China. *Nutrient Cycling in Agroecosystems*, *76*(1), 81–94. https://doi.org/10.1007/s10705-006-9042-x

Yau, S. K., Bounejmate, M., Ryan, J., Baalbaki, R., Nassar, A., & Maacaroun, R. (2003). Barley–legumes rotations for semi-arid areas of Lebanon. *European Journal of Agronomy*, *19*(4), 599–610. https://doi.org/10.1016/S1161-0301(03)00006-6

Zander, P., Amjath-Babu, T. S., Preissel, S., Reckling, M., Bues, A., Schläfke, N., Kuhlman, T., Bachinger, J., Uthes, S., Stoddard, F., Murphy-Bokern, D., & Watson, C. (2016). Grain legume decline and potential recovery in European agriculture: a review. *Agronomy for Sustainable Development*, *36*(2), 26. https://doi.org/10.1007/s13593-016-0365-y

Zhang, F., & Li, L. (2003). Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. *Plant and Soil*, *248*(1/2), 305–312. https://doi.org/10.1023/A:1022352229863

Capítol 5. Survey of soil fertility in irrigated Mediterranean systems: Challenges and constraints

5.1 Introduction

The positive effect of application of manure and other organic amendments is well studied, as it increases crop yields by providing macro and micronutrients (Ovejero *et al*., 2016; Martínez *et al*., 2017; Perramon *et al*., 2018), improves soil physical properties (Domingo *et al*., 2016; Valdez *et al*., 2020) and increases microbial activity (Yagüe *et al*., 2016; Risberg *et al*., 2017). Negative effects have also been associated to the agricultural use of these products. A great part research of the last century has been focused on the agricultural/environmental effects of nitrogen (N), and its agricultural use was regulated through the Nitrates Directive (OJ, 1991). However, the agricultural use of phosphorus (P) is also considered a big challenge to prevent, essentially, eutrophication (Bennett *et al*., 2001). The soil P accumulation, and its potentially risk to be lost to water bodies, is often linked to high livestock density areas with an over-use of manure applications that commonly exceed crop needs (Pote *et al*., 1996; Sims *et al*., 1998; Jalali, 2007; Tóth *et al*., 2014; Einarsson *et al*., 2020, Roswall *et al*., 2021). Although the transport of P in soils is primarily attributed to erosion and runoff (Sharpley & Halvorson, 1994; Pote *et al*., 1996, Hugues *et al*., 2000; Schröder *et al*., 2010), some authors (Sims *et al*., 1998; Hooda *et al*., 1999; Maguire & Sims, 2002) are concerned about the potential risks of losses by leaching, also in calcareous soils (Robbins & Smith, 1977; Beauchemin *et al*., 1998; Schoumans *et al*., 2015), which must be a matter to be considered to prevent undesirable effects. Other studies prove a connection of organic amendments, e.g. sewage sludge, to heavy metals (Alloway & Jackson, 1991). Some of these elements (Cu, Zn), which are also considered as essential oligoelements for plant development, are studied in soils because of their high concentration in manure (Mantovi *et al*., 2003; Xu *et al*., 2013), especially in pig slurries or solid fractions obtained after a separation treatment. Nevertheless, mineral fertilizers are also associated to soil pollution because of heavy metals like Cd (Römkens *et al*., 2018; Kubier *et al*., 2019; de Vries *et al*., 2022).

In contrast to nitrogen or heavy metals for manure and sewage sludge, respectively, there is no EU regulation concerning to P in agricultural soils, and only some countries or regions have implemented restrictions to minimise losses and ensure best agricultural practices (Amery & Schoumans, 2014; Garske *et al*., 2020, Rosemarin *et al*., 2021). Some of those regulations (e.g. Germany or Denmark) have been recently modified (Barreau *et al*., 2018). Catalonia (NE Spain) is one of the top regions in the EU for livestock farming, with a clear specialisation in the swine sector (Eurostat, 2021a). Manure application is the main P input on agricultural land, where 47 % of the total P applied comes from livestock. The calculated surplus for this NUTS-2 region is about of 18.1 kg of nutrient per ha, a value substantially deviated from the national average (MAPAMA, 2018) and that situates Catalonia in one of the EU regions with higher P-surplus (Eurostat, 2021b). According to the information from the calculated balance, the use of P from manure in Catalonia should be enough to satisfy crop P needs. It is important to underline that it is the only Spanish region that implements compulsory measures related to P fertilisation for crop production systems (DOGC, 2019), by setting a warning limit of P (Olsen) of 80 mg P/kg and an infraction threshold of 150 mg P/kg.

There are plenty of methods that have been used to evaluate P in the soils based on different purposes (agronomic and/or environmental) and applied at different scales (experimental, local, regional, national). The use of chemical methods to analyse P based on single extractions is worldwide developed, but as Renneson *et al*. (2016) pointed out, some of them are more focused to agronomic purposes (e.g. Olsen or Bray, to determine available P), while others are more utilized to determine environmental impacts (e.g. water or $CaCl_2$ extraction, to determine soluble P). A combination of both of them (e.g. available P vs. soluble P) is usually used to study the possible risk of P loss from soil to water (Sharpley *et al.*, 1996; Wang *et al.*, 2010), where a critical P value, known as the change point or threshold value, is obtained as an indicator of possible P desorption from the soil matrix, and a consequently mobilisation of this element to deeper horizons or drainage systems. Although the matter of P leaching is being studied since the 70s (Logan & McLegan, 1973; Novak *et al.*, 1975), the concept of change point was introduced by the 90s (Heckrath *et al.*, 1995; Sims *et al.*, 1998). However, more information at farm/local scale is required, especially from calcareous areas submitted to intensive livestock farming, in order to quantify the real risks that they might cause to water bodies.

The purpose of this study was to characterise the soils from an irrigated cereal crop area to identify nutrient constraints or challenges with a special attention to available P (AvP) as a reliable indicator related to the use of manure, and to associate it to potential benefit/risk factors that could enhance/compromise soil health. The results of this study might help policy makers to implement management fertilization practices to ensure a better use of nutrients, preserve soil fertility in the long term, and prevent potential losses to water bodies.

5.2 Materials and methods

5.2.1 Study area

As part of a demonstrative project (LIFE12 ENV/ES/647) within the EU LIFE Programme, a fertilization assessment was carried out in an agricultural area located in the Ebro river basin (NE Spain) (41°47'12" N and 0°40'59"E) during the period 2014-2018. All the data obtained, which were also complemented with other information from the same area, has been used as the source for this work.

The climate of the area is Dry Continental Mediterranean characterized by hot summers (average of 23-25 ºC), cold winters (average of 3-5 ºC), and a low annual rainfall (average of 400-550 mm). Soils in that region were formed over detritic and terrigenous materials on the residual platforms of some alluvial fans originated in the area (Ascaso *et al.*, 1991). The most part of them are deep soils, calcareous, with a loam texture and classified as Typic Calcixerept (Soil Survey Staff, 2014).

Although the region is mainly cultivated under dryland conditions (59 % according to DACC, 2020), the studied area is fully irrigated by the Algerri-Balaguer channel, where grain cereals, mainly included in double annual crop rotation of corn and barley, are the most common crops. The affected municipalities are characterised as a medium index of livestock load (DOGC, 2019) with intensive pig farming as the most representative animal rearing in the area.

5.2.2 Survey

Within the framework of the project, information from 35 farmers was collected to a better understanding of the nutrient management in the area. The survey included questions about the farmers’ activity that generated more incomes, whether they owned livestock, the use of contractors to apply fertilizers or manure, or the type of fertilization. As a result of this work, we know that agriculture was the main source of income (76 %), and more than one third of the respondents raised animals, mainly swine livestock. Only 17 % of farmers did not use manure or any organic amendment, which indicates the high pressure of livestock in the region. The use of contractors is common in the area (86 %), where harvesting and the application of fertilizers, manure or pesticides are the main external tasks. With regard to fertilizer assessment, a large proportion of respondents (90 %) expressed no needs for technicians or extension services.

5.2.3 Soil sampling

A first set of sampling at farm-scale was conducted during the period 2014-2018, previously to crop fertilization, over a cultivated area of 733 ha owned by 35 farmers, to evaluate different chemical soil parameters on 93 plots. Composite samples included 8 sub-samples for every 4 hectares.

By combining the results obtained from the first soil monitoring (2014) with the information collected from the survey, a multiple analysis was performed to evaluate the relationship among soil general parameters: pH, electrical conductivity (EC 1:5 w/v), calcium carbonate equivalent (CCE), organic carbon (OC), available P (AvP, Olsen) and available K (AvK, ammonium acetate extraction) and to confirm the use of AvP as an adequate indicator to measure the pressure from the use of fertilizers on irrigated crops in calcareous soils. As a result, a selected second set of 13 complementary samples was obtained to analyze other variables related to the potential benefits and risks that could be associated to the use of manure and other organic amendments, which included macronutrients (total N and P, and AvP), microelements (total B, Fe, Cu, Zn, and available Cu, Zn, Mn) and heavy metals (total Co, Pb, Cr, Hg, Cd).

Finally, in order complete the P assessment, 30 samples were analyzed (total P and AvP) to study a possible displacement from the topsoil (0-30 cm) to deeper layers (30-60 cm).

5.2.4 Laboratory determinations

Soil samples were transported from fields to the laboratory the same day of sampling and maintained in the fridge at 4 ºC before being analyzed. Once dried and sieved, they were submitted to different determinations: pH (ext 1:2.5 H_2O), EC (25 ºC, ext 1:5 H_2O), oxidizable C (Walkley & Black, 1934), CCE (Bernard calcimeter), total N (TN) (Kjeldahl method) and total P (TP) (acid digestion), AvP, AvK, available Cu (AvCu), Zn (AvZn) and Mn (AvMn) (DTPA-extraction), total B, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb and Zn (acid extraction).

5.2.5 Statistical analysis

We used multivariate statistical methods for a more comprehensive evaluation of data visualization. We analysed two datasets. The first monitoring data set that included the variables AvP, AvK, CCE, EC, OC and pH. The second data set included the variables TN, TP, AvP, AvK, Cu, Zn, AvCu, AvZn, AvMn, and total Mn, Cd, Co, Cr, Fe, Hg, Ni and Pb. Principal component analysis (PCA) was performed on both datasets.

The called parallel analysis for component retention (Horn, 1965), where adjusted eingenvalues >1 indicate dimensions to retain, was applied. From such analysis, scree plots were generated using psych package in R.

Nonlinear models were used for describing the P movement in soil: split-line model; exponential model, lineal plateau model, and logarithmic model.

5.3 Results

5.3.1 General soil monitoring

Available nutrients (0-30 cm) showed a very wide range of values (Tab. 5.1) with a minimum of 6.2 and 71 mg P/kg and a maximum of 134 and 786 mg K/kg. Soils had a very low soil organic matter content (below 1.5 % of OC), especially considering that soils have been under irrigation for a 20-year period. Values of CCE were high (median of 26 %), the EC 1:5 alerts about potential restrictions on crop development (percentile 75th of 0.81 dS/m), and the pH ranged from slightly to strongly alkaline, but all the three parameters are considered normal according to the area.

Tab. 5.1 Descriptive statistics of soil general chemical parameters at 0-30 cm depth

	AvP (mg/kg)	**AvK** (mg/kg)	**CCE** (%)	**EC (1:5, w/v)** (dS/m)	**OC** (g/kg)	**pH (1:2.5, w/v)**
Mean	41.5	258.0	25.4	0.65	1.19	8.1
Std. deviation	31.1	130.7	8.4	0.67	0.29	0.2
Percentile 25th	18.0	154.0	24.0	0.24	0.98	8.0
Median	31.0	237.0	26.0	0.31	1.15	8.2
Percentile 75th	58.0	338.0	31.0	0.82	1.35	8.3
Minimum	6.2	71.0	5.0	0.2	0.7	7.7
Maximum	134.0	786.0	42.0	2.7	2.3	8.5
Count	93	93	93	93	93	93

AvP: available P (Olsen method); AvK: available K (ammonium acetate extraction); CCE: calcium carbonate equivalent (Bernard calcimeter); EC: electrical conductivity (1:5, w/v); OC: organic carbon (Walkley-Black method).

The PCA conducted over 93 samples shows that two components explain almost the 70 % of the data variability (Tab. 5.2). In order to determine the optimal number of PC, the eigenvalues have been ordered from the largest to the smallest. The number of components is determined at the point beyond which the remaining eigenvalues are all relatively small and of comparable size (Jolliffe, 2002; Peres-Neto *et al.*, 2005). The parallel analysis method for component retention (Fig. 5.1) corroborates two dimensions to retain (adjusted eigenvalues >1). Thus, two factors are suggested as the optimal number of components for this dataset.

Tab. 5.2 Principal component analysis of soil general chemical parameters for the six principal components

Principal Component	Eigenvalue	Variability (%)	Cumulative (%)
PC1	2.3202	38.67	38.67
PC2	1.7654	29.42	68.09
PC3	0.9793	16.32	84.42
PC4	0.4029	6.71	91.13
PC5	0.3365	5.61	96.74

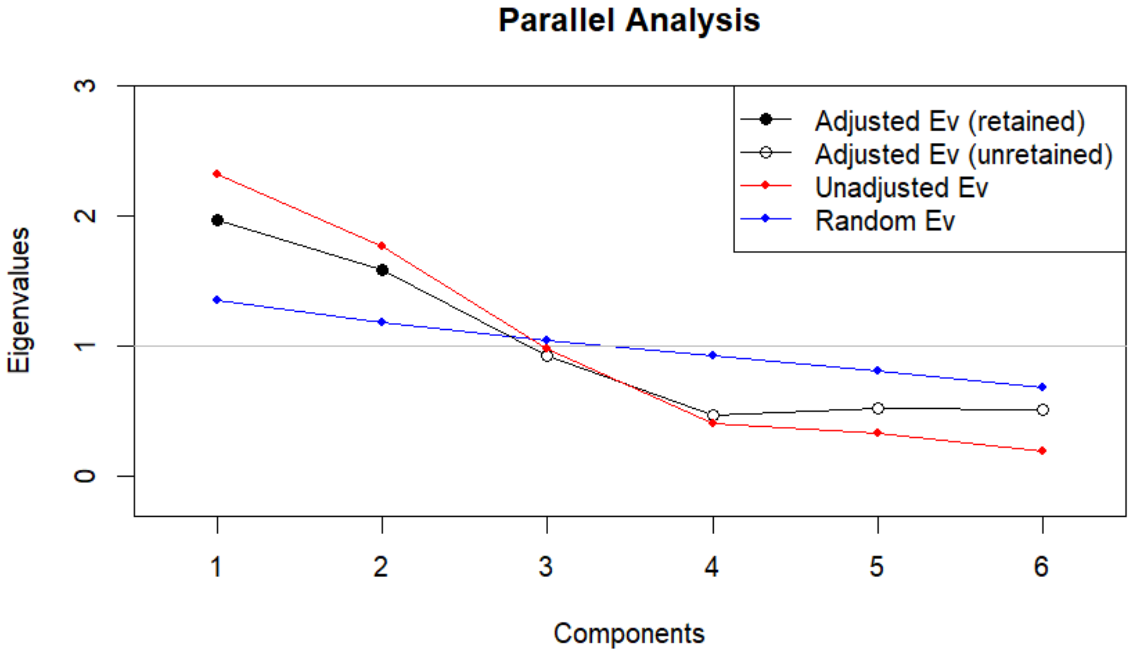

Fig. 5.1 Parallel analysis of the PCA on simulated data with two true components underlying six variables. Non-retained components are marked with a hollow circle on the adjusted eigenvalues curve. Note that the cut-off black solid line runs through the elbow of eigenvalue (Ev) actual data (black line).

The multivariate analysis reveals a good connection among some of the studied variables (AvP, AvK and OC). The first component (PC1) accounts for 38.7 % of the variability, is mainly determined by parameters related to the application of manure or other organic amendments (Fig. 5.2). The second component (PC2), accounts for the 29.4 % of the variability, related to variables like pH or CE, and with a lack of relationship with the use of fertilizers in our agricultural system.

Distribution of samples on the biplot (Fig. 5.2) indicates that fields belonging to farmers with a rearing activity have higher soil contents of OC, AvP and AvK that the rest. The chart represents, on the right side of the PC1 axis, around 30 % of samples from crop-livestock farming system vs. 9 % from crop farming system, and 8 % vs. 29 %, respectively, on the left side. It has to be considered that 24 % of samples were classified inside a group of an undefined farming system.

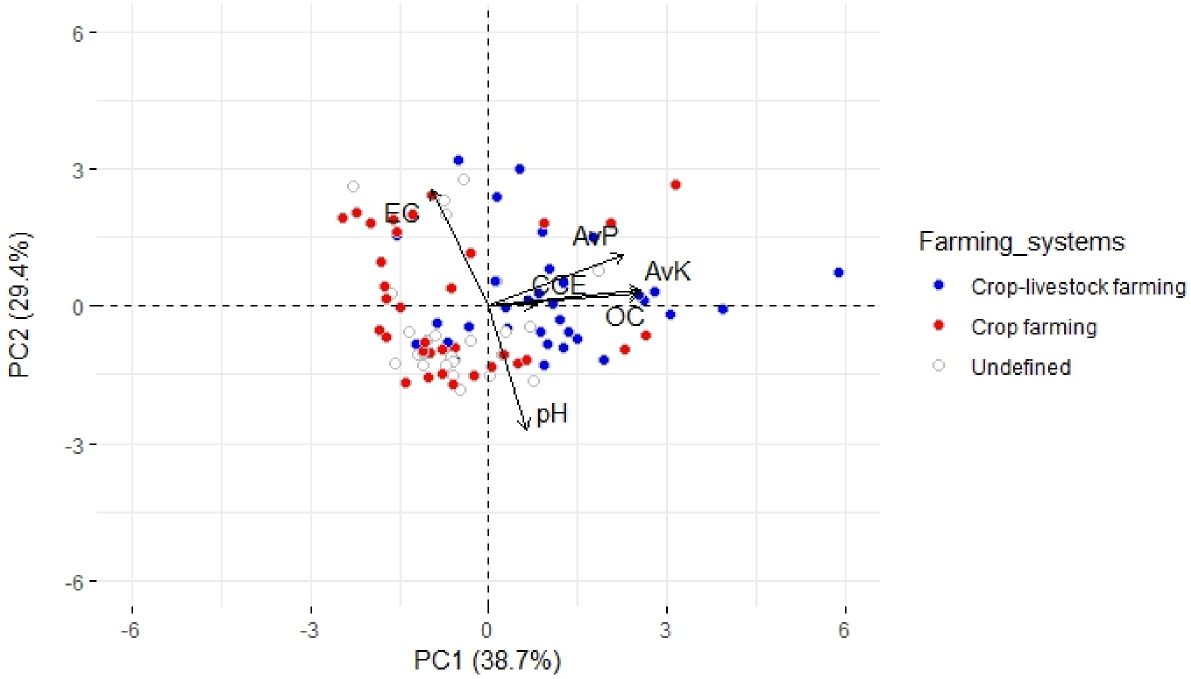

Fig. 5.2 Principal component analysis biplot (PC1 vs. PC2) of soil general properties according to the farming system. Letters represent the 6 studied variables: available P (AvP), available K (AvK), calcium carbonate equivalent (CCE), electrical conductivity (EC, 1:5 w/v), organic carbon and (OC) and pH. Blue, red and white circles represent 93 fields under a mixed crop-livestock farming, crop farming and undefined systems, respectively.

The dispersion graph (Fig. 5.3) represents the wide AvP and AvK range of the studied cases. They also allowed to differentiate the farming systems identified in the survey. Most of the farmers who combine rearing animals with crop farming (named as “crop-livestock farming”) are on the upper quadrant side and more dispersed, which means that they exceed the recommended (Andrades & Martínez, 2022) soil contents of AvP (>25 mg P/kg) and AvK (>295 mg K/kg) for crop growing. Quite the opposite, farmers without livestock (named as “crop farming”) are clearly distributed on the lower left quadrant, with levels below the previously mentioned threshold.

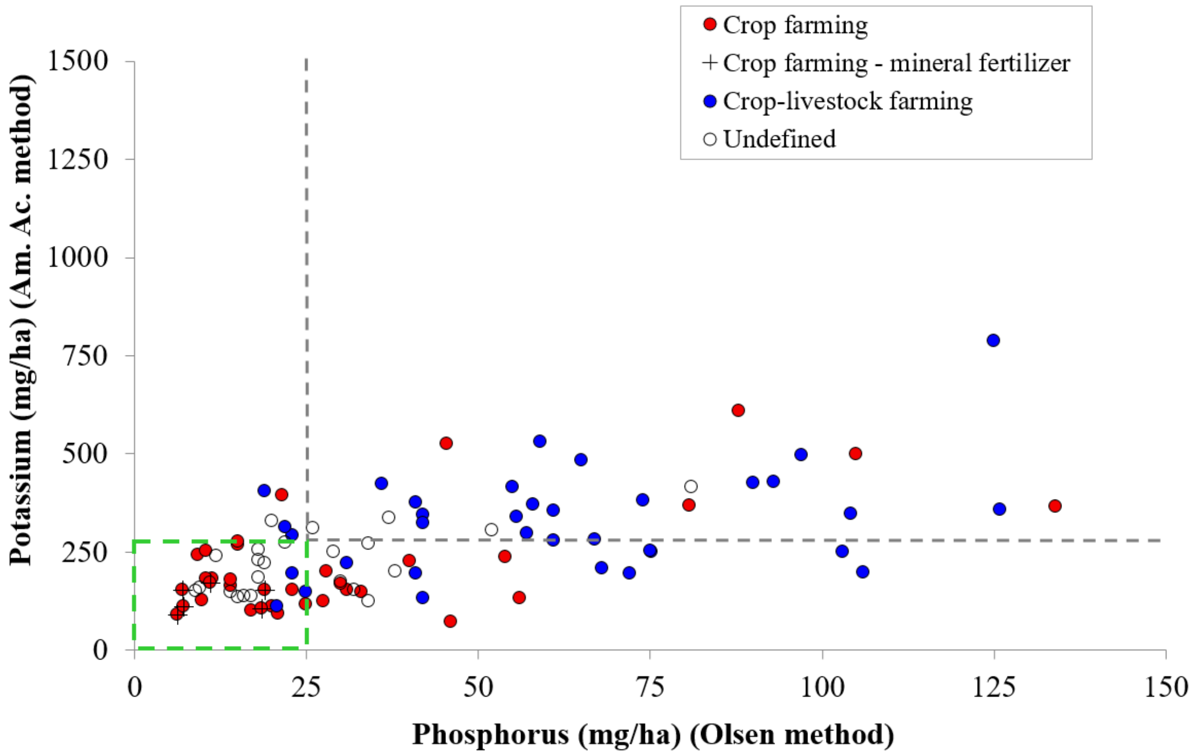

Fig. 5.3 Dispersion of available P (AvP) and K (AvK) from topsoil samples (0-30 cm). Blue, red and small-grey circles represent 93 fields with mixed crop-livestock farming, crop farming and undefined systems, respectively. A black cross is used to identify samples that exclusively used mineral fertilizers, all of them are crop farming systems. The vertical and horizontal grey dotted lines represent the threshold for AvP and AvK soil contents, respectively, in the area. The green lower left quadrant shows the area with no excess of available nutrients.

After this first approach, the use of AvP as a potential indicator of the fertilization management on calcareous soils was reinforced. Although AvK could also have been taken into account, it was rejected because the higher needs of the crops and the interference from other management practices (e.g. exportation/incorporation of straw), which might influence on it.

5.3.2 Nutrients and heavy metals monitoring

The second and more oriented soil monitoring, according to the AvP results from the first sampling, resulted again in a wide range of values for all the studied variables.

It is remarkable the high content of AvP where about half of the cases exceed the warning level of 80 mg P/kg and where the threshold of 150 mg P/kg is almost reached by at least one sample. According to the heavy metals and some microelements, although no sample exceeds the regulation limits, it should be noticed that elements like total Cu, Ni or Zn contents are getting close to them in a few cases.

Tab. 5.3 Descriptive statistics of soil (0-30 cm) nutrients and heavy metals.

Variable	**Macronutrients**			**Micronutrients**									**Heavy metals**				
	Kjeldahl method	**Acid digestion**	**Olsen method**	**DTPA-extraction (mg/kg)**			**Acid-extraction (mg/kg)**						**Acid-extraction (mg/kg)**				
	N	**P**	**P**	**Cu**	**Mn**	**Zn**	**B**	**Cu**	**Fe**	**Mn**	**Ni**	**Zn**	**Cd**	**Co**	**Cr**	**Hg**	**Pb**
	(g/kg)	(mg/kg)	(mg/kg)	(mg/kg)			(mg/kg)						(mg/kg)				
Mean	1.5	1044	72.9	2.9	13.3	9.0	17.0	27.0	19298	448	19.9	90.2	0.12	7.8	24.1	0.21	12.1
Std. deviation	0.4	278	43.2	1.6	8.7	2.2	3.1	5.7	2686	55	2.8	28.0	0.06	1.0	3.5	0.15	1.7
Percentile 25th	1.2	892	34.9	1.7	9.3	7.5	14.0	21.9	18364	416	18.6	68.7	0.07	7.3	21.7	0.12	11.0
Median	1.5	1048	86.3	3.1	12.9	9.5	17.0	28.9	20066	453	19.2	88.4	0.13	7.9	22.8	0.16	12.6
Percentile 75th	1.7	1221	100.7	4.4	22.3	9.9	19.0	30.8	20590	489	21.9	114.8	0.17	8.4	27.2	0.25	13.7
Minimum	1.0	564	8.8	0.5	1.0	5.5	13.0	18.3	14545	366	15.2	50.0	0.02	5.7	18.4	0.04	8.8
Maximum	2.0	1493	142.7	4.8	24.4	13.1	22.0	36.1	23505	546	25.4	130.0	0.20	9.2	29.4	0.59	14.0
Count	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13
<u>Threshold:</u>																	
OJ, 1986								50-140	-	-	30-75	150-300	1.0-3.0	-	100-150	1.0-1.5	50-300
BOE, 1990								50-210	-	-	30-112	150-450	1.0-3.0	-	100-150	1.0-1.5	50-300
DOGC, 2019			80/150														

The PCA analysis from the studied soils showed that five factors are able to explain almost the 93 % of the variability (Tab. 5.4), where two components explained around 70 %. By ordering the eigenvalues and using the parallel analysis (Fig. 5.4), two components were considered as the optimal for this data set.

Tab. 5.4 Principal component analysis of nutrients and heavy metals in the second soil sampling

Principal Component	Eigenvalue	Variability (%)	Cumulative (%)
PC1	6.8205	40.12	40.12
PC2	4.9551	29.15	69.27
PC3	2.0724	12.19	81.46
PC4	1.1588	6.82	88.27
PC5	0.8676	5.10	93.38

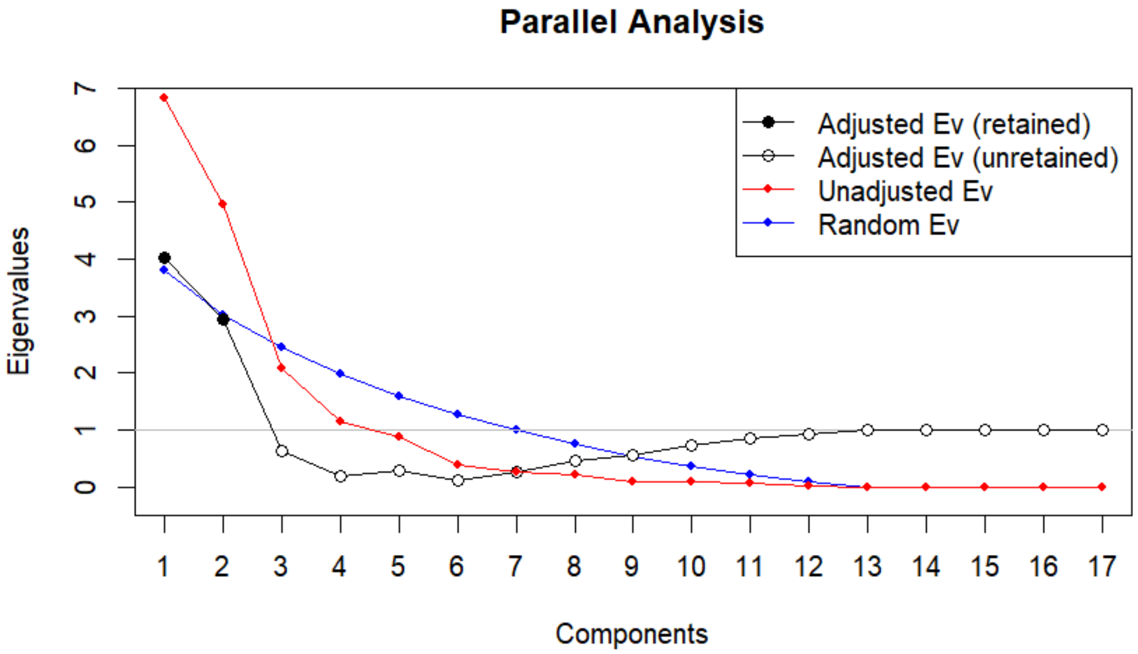

Fig. 5.4 Parallel analysis of the PCA on simulated data with two true components underlying 17 variables. Non-retained components are marked with a hollow circle on the adjusted eigenvalues curve.

A second biplot chart (Fig. 5.5) indicates how the group of variables related to the use of organic amendments (TN, TP, AvP, AvK, AvCu, AvZn, AvMn) is clearly associated to the first component (PC1), which is representative of 40.1 % of the variability. The use of mineral fertilizers is also represented by PC1, but antagonist to the mentioned group, and seems to have a relation with the levels of Cd in soil. Most of the total heavy metals analyzed (Co, Cr, Fe, Mn, Ni, and Pb) are associated with second component (PC2), which explains 29.1 % of the variability.

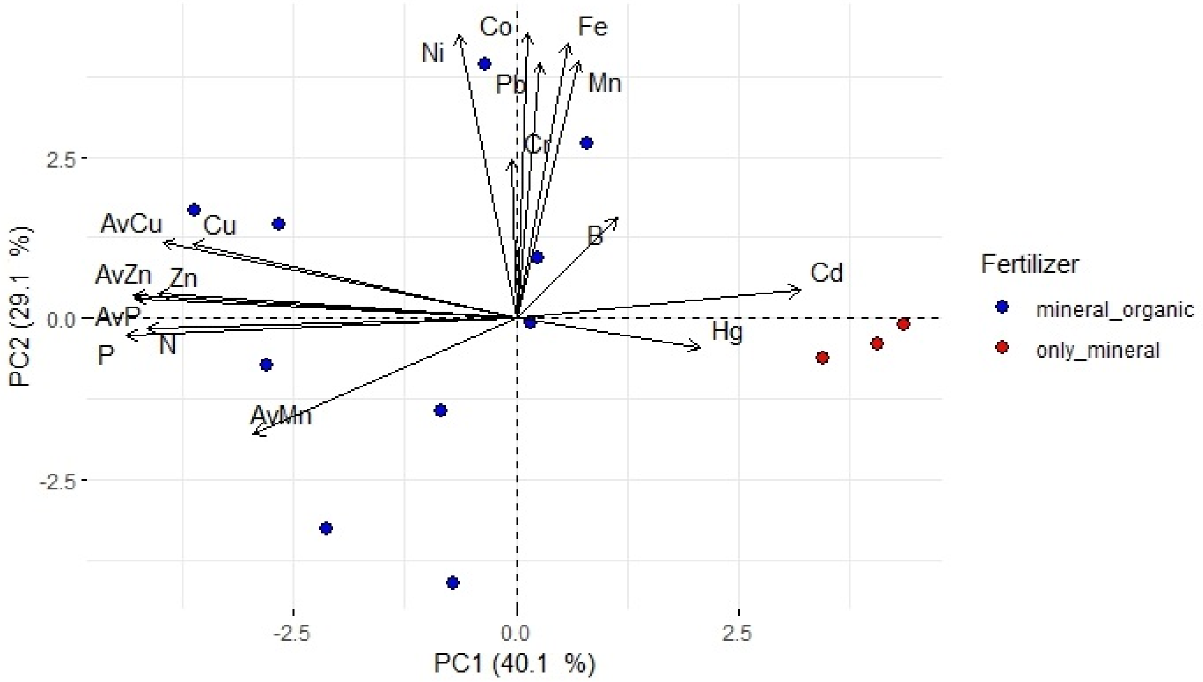

Fig. 5.5 Principal component analysis biplot (PC1 vs. PC2) of heavy metals and nutrient variables according to the type of fertilizer. Letters represent the 17 studied variables. Red and blue circles represent 13 soil samples from plots that received only mineral fertilizers or combined organic and mineral fertilizers, respectively.

5.3.3 Phosphorus mobility

Plots that received only mineral fertilization showed lower AvP at both measured depths (Fig. 5.6). The AvP values decrease in depth (0-30 cm > 30-60 cm) (Fig. 5.3, Fig. 5.6). The relation AvP between the two depths is no constant and it is affected by the amount of P at the topsoil, since at certain content of this element on the upper layer (0-30 cm), it increases in the layer below (30-60 cm).

The relationship of AvP at both depths is well correlated by using a split-line model (R^2=0.85) (Fig. 5.7 A) and also by an exponential model (R^2=0.84) (Fig. 5.7 B). The data distribution shows more dispersion as the contents of P increase in the soil.

A positive and non-linear relationship is obtained when the values of AvP from the topsoil (0-30 cm) are compared with the TP at the same depth. Although the lineal-plateau model shows a good correlation (R^2=0.66) with a high slope below the value of 53.0 mg/kg of AvP at 0-30 cm (Fig. 5.7 C), the logarithmic model fits better with the data (R^2=0.73) and indicates how TP at 0-30 cm slows down beyond 50-60 mg/kg of AvP at 0-30 cm (Fig. 5.7 D). Thus, a “changing point” or “changing zone” is observed around 50-90 mg/kg, depending on the model.

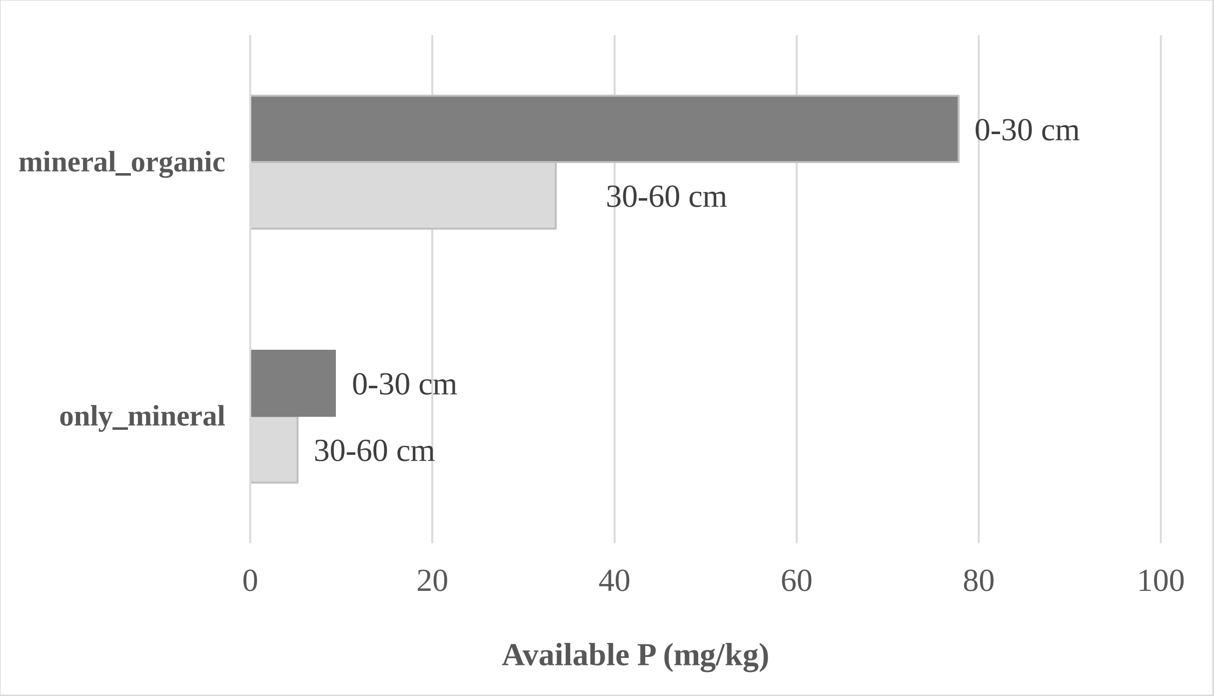

Fig. 5.6 Average of the AvP (mg/kg) at 0-30 cm and 30-60 cm for 30 plots that received only mineral fertilizers and plots that combined mineral with organic fertilizers.

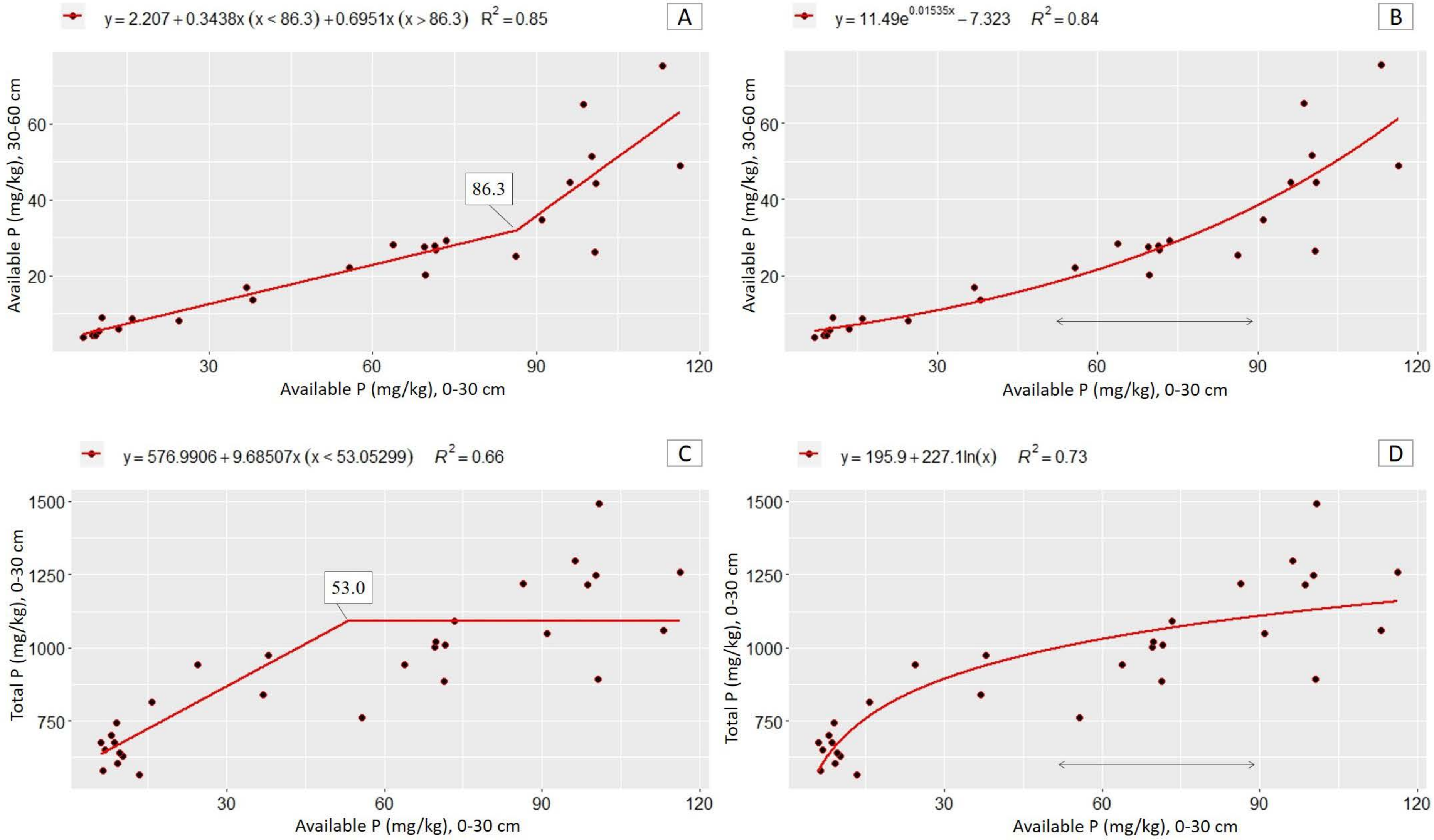

Fig. 5.7 Nonlinear models for describing the P movement in 30 soil samples, by comparing AvP (mg/kg) at 0-30 cm and AvP (mg/kg) at 30-60 cm (A, split-line model; B, exponential model) and AvP (mg/kg) and TP (mg/kg) both at 0-30 cm (C, lineal plateau model; D, logarithmic model).

5.4 Discussion

5.4.1 Soil fertility according to the farming system

Organic amendments as manure, treated manure, agrifood waste or sewage sludge are examples of valuable nutrient sources that can be used in agriculture to enhance soil fertility and maintain crop production, in a circular economy framework (Ghisellini *et al*., 2016; Stamm *et al*., 2021). Within this context, and as a result of the local monitoring carried out in the present study, a high variation on soil parameters was detected (Tab. 5.1), where some of them may be derived from the fertilization management and others do not (Fig. 5.2).

The effect of a continued use of manure and other amendments seems to have an effect on the accumulation of OC, AvP and AvK (Fig. 5.2), which is in line with results from authors who worked with long-term experiments. Yagüe *et al*. (2012) and Martínez *et al*. (2020) supported moderate to large soil OC increments with liquid swine manure applications, while Bosch-Serra *et al*. (2020) reported an annual boost of 2.5 % by using dairy cattle slurry. However, soil pH, EC and CCE are probably related to the intrinsically conditions of the area, as appear to be disconnected from the fertilization management (Fig. 5.2). Detected values of soil EC beyond 0.5 dS/m indicate that farmers must pay attention to salinity affectation. In some cases, maximum levels reached values around 2.2, which is possibly related with the presence of gypsum in the region (Herrero *et al*., 1996). The low relevance of EC is in line with results obtained by the application of manure and mineral fertilizers at high continued rates (Yagüe *et al*., 2012; Yagüe & Quílez, 2013; Bosch-Serra *et al*., 2020; Martínez *et al*., 2020). The pH and the CCE were both in concordance with the soil types described in the soil map 1:25000 of Catalonia (Ascaso *et al*., 1991), which were formed over detritic and terrigenous materials on the residual platforms of some alluvial fans originated in the area.

Soil fertility in the area seems to be unbalanced according to the main studied macronutrients, since a large number of plots show fertility contents out of the recommended levels (Andrades & Martínez, 2022). That suggests there are some external factors that may have some influence on the soil accumulation of essential nutrients for crops. One of this factors could be the farming system. This suggestion is partially confirmed (Fig. 5.3) as a high dispersion and range of AvP is observed on mixed crop-livestock farming systems. On the contrary, crop farming systems show more concentred values of this element, and mainly below the pointed limit. A similar pattern is observed on AvK contents, but with a lower range. The biplot (Fig. 5.2) confirms that available macronutrients are more associated to farmers who combine livestock with crop farming. It is surprising how around 20 and 30 % of the sampled plots have deficiency of AvP (<16 mg/kg) and AvK (<156 mg/kg), respectively, in an area with a considerable livestock density. This data is even more shocking if it is considered that more than half and one third of the studied cases exceed the upper threshold of >25 and >295 mg/kg, respectively.

5.4.2 Benefits and risks of different fertilizer's management

The source of the nutrients used to fertilize crops in the studied area seems to have an influence over the soil characteristics (Fig. 5.3, Fig. 5.5), which may be induced by the type of farming system. As a consequence, both farming systems and type of fertilizers should be considered as relevant aspects in terms of potential benefits and risks to the agriculture and the environment.

The associated benefits from the use of organic amendments (e.g. livestock manure, provides nutrients and organic matter) is well studied for plenty of authors (Powlson *et al.*, 2012; EU Nitrogen Expert Panel, 2015; Johnston & Poulton, 2019; Chowdhury & Zhang, 2021), who report the increase of macronutrients, like N, P and K, and the accumulation of OC, which it is corroborated in the current analysis (Fig. 5.5). According to Bosch-Serra *et al.* (2020), liquid manure improved P and K soil bioavailability, and soil organic matter light fraction, that is a parameter well correlated with water-aggregate stability (Yagüe *et al.*, 2012; Yagüe & Quilez, 2013). However, plots with exclusive mineral fertilization should build up their soil P, K and OC contents from deficiency to maintenance levels (Andrades & Martínez, 2022) to avoid soil and plant side-effects.

The high variability on the contents of soil micronutrients, such as Cu, Mn and Zn, found after the second monitoring (Tab. 5.3), has a connection to the fertilization management. If no organic amendments are applied, deficiency on these oligoelements is associated to high pH and bicarbonates, and high clay contents (Mousavi *et al.*, 2013; Ballabio *et al.*, 2018), soil characteristics that reduce availability for crops, especially in cold conditions, when root growth is limited and the release from organic matter is reduced (Mousavi *et al.*, 2013). This is corroborated in our study with samples that received only mineral fertilization (Fig. 5.5). Thus, in areas with low content of these micronutrients (Rodríguez-Martín *et al.*, 2009; Gómez-Miguel & Sotés, 2014; Ballabio *et al.*, 2018), the application of manure should help to increase that levels and reduce the costs from mineral fertilization supplies.

Negative effects as a result of inadequate agricultural practices may also be taken into account as they may impact on soil health or water bodies. The main risks associated to organic amendments, nitrates water pollution and eutrophication (Bomans *et al.*, 2005; Peyraud & MacLeod, 2020), are linked to surplus of nitrates, and nitrates and phosphates, respectively, that move from soils to water bodies. Nitrogen and P in our study show a positive connection with mix crop-livestock farming systems (Fig. 5.2, Fig. 5.3) and a negative correlation with the use of mineral fertilizers (Fig. 5.3, Fig. 5.5). Relevant residual mineral N contents in the soil have been reported after continued application of manure at high rates (Berenguer *et al.*, 2008a; Ovejero *et al.*, 2016; Perramon *et al.*, 2018; Bosch-Serra *et al.*, 2020), but also significant values were found with mineral fertilizers (Biau *et al.*, 2013; Martínez *et al.*, 2017). The use of multi-isotopic and molecular tracking methods could help to determine the source of contamination (Carrey *et al.*, 2021). A challenge to reduce this potential impact should be a better management of residual N and P (Schröder *et al.*, 2011; Webb *et al.*, 2011; EU Nitrogen Expert Panel, 2015; Schoumans *et al.*, 2015; Stamm *et al.*, 2021), which would increase the efficiency of these nutrients in agriculture.

Intensive livestock feeding introduces essential elements (e.g. Cu, Mn and Zn) in animal diets as growth promoters or because of their medical properties, among other characteristics (Poulsen, 1998; Bernhoft *et al.*, 2014). This common practice has driven to a relevant content of such elements in the manure, which is ultimately accumulated in agricultural soils after their application. This casuistic, and more especially in the case of Zn, can be observed in our study (Fig. 5.5), where the accumulation of this oligoelements in the topsoil is in relation with the application of manure or other organic amendments. These results are in line with other authors (Berenguer *et al.*, 2008b; Martínez *et al.*, 2020) who obtained similar values of total Cu (~24 mg/kg) and Zn (~90 mg/kg), and even higher values of extractable (EDTA) Cu (~8 mg/kg) and Zn (~20 mg/kg) by applying 50 m^3/ha of liquid swine manure. Contrary to that, Bosch-Serra *et* *al*. (2020) reported no differences on soil Cu and Zn contents when applying dairy cattle slurry, even they showed a trend to increase with the dose. It is important to underline that the obtained results are far away from the threshold established in the current legislation (OJ, 1986; BOE, 1990), so there is no risk of contamination that could compromise the soil health or the food production (Mantovi *et al.*, 2003; Martínez *et al.*, 2020). In the case of Zn, some authors (Iglesias *et al.*, 2018; Zaragüeta *et al.*, 2021) found a boost of this element when using sewage sludge after 15 years and 26 years of continued application, respectively, so this could also be another source in organic amended soils. According to Mn, our results are in the lower part of the range of total Mn values cited in the reviews made by Millaleo *et al*. (2010) and Gómez-Miguel & Sotés (2014), but higher than the obtained by Bosch-Serra *et al*. (2020) with dairy cattle slurries (334 mg/kg), which could be explained by the questioned high supplementary levels added in pig diets (Kerkaert *et al*., 2021).

Cadmium content from mineral fertilizers (phosphate fertilizers) has been under discussion during the implementation of the new EU fertilizers regulation (OJ, 2019), although this matter concerned the EU since the 90s, when some state members set up national regulations on this element (Bomans *et al*., 2005). The higher value obtained in our monitoring was ten times higher than the minimum (Tab. 5.3), which indicates that probably some anthropogenic source was influencing this results. The use of mineral fertilization was associated with soil total Cd contents (Fig. 5.5). Although such results were still distant from the current legislation (OJ, 1986; BOE, 1990), and it is not enough information about the history of the sampled soils, it is important to continue monitoring this trace element as its increase should be considered a potential risk for the soil health and the food chain.

The rest of the soil microelements and heavy metals analysed (B, Cr, Co, Fe, Mn, Ni, and Pb) show no association to the fertilization practices (Fig. 5.5), and are probably related to edaphogenic causes. These results are partially in line with Bosch-Serra *et al*. (2020), who indicated that the soil heavy metal content was not affected by the use of dairy cattle slurries and it can be considered similar to the soil background for As, Cd, Co, Cr, Pb, V, Cd, Cu, Fe and Zn. Other studies (Iglesias *et al*., 2018, de Vries *et al*., 2022) reported a connection between Pb and sewage sludge. The main trace elements sampled were similar to the results from a Spanish survey (López-Arias & Grau-Corbí, 2004), which was performed also in the province of Lleida, where the present study was located. There is no data about previous amendments that some plots could have received decades ago, which could have disturbed the results. Again, it is important to emphasize that none of the samples exceeded the current soil threshold established in the EU (OJ, 1986) and Spain (BOE, 1990).

5.4.3 Phosphorus vertical displacement on calcareous soils

The first indication of P movement from top to down layers is observed at Fig. 5.6, by comparing plots that only have received mineral fertilizers against other who have eventually combined mineral with organic amendments. First case of farmers tends to better adjust P needs for crop development (Cela *et al*., 2010; Goss *et al*., 2013), which indicates that its soil P contents, at both depths, are probably close to the background level in the area. By opposite, the second case corroborates a change on the basal P levels caused by organic P supplies, which are observed at both layers. The AvP at 30-60 cm increased by 7 times, so this result points out the vertical movement of this element on calcareous soils. Other authors (James *et al*., 1996;

Sims *et al*., 1998; McDowell & Sharpley, 2001) reported TP and AvP accumulations at deeper layers on manured soils in comparison to poor P or unmannered soils.

The risk of vertical P soil movement is positively related to the amount of AvP in the topsoil. Our data indicate a rapidly increase on the accumulation of AvP at 30-60 cm beyond 86.3 mg/kg (Fig. 5.7 A), showing a major release of P. That could be supported by the not linear accumulation of TP at 0-30, meaning that phosphates become saturated (Bomans *et al*., 2005) as the soil cannot retain more TP at such depth (Fig. 5.7 C). Once the topsoil reached the limit capacity to retain P, a movement of soluble organic P via dissolved OC or colloidal particles (James *et al*., 1996; Chardon *et al*., 1997) may occur through macropores (Jarvis, 2007; Freiberger *et al*., 2014), which presence is influenced by fertilization (Yagüe *et al*., 2016). Once the subsoil is enriched, P mineralization could release P (James *et al*., 1996). Therefore, under the calcareous conditions of the study, we conclude that soils with AvP contents between the range of 60-80 mg/kg seem to be at certain risk of being displaced to deeper layers, which was in line with values from authors who used the Olsen-P method like Heckrath *et al*. (1995) (60 mg/kg) and Jalali & Jalali (2017) (80.3 mg/kg). McDowell *et al*. (2001) obtained a high variability with arable crops (20 to 60 mg/kg).

Phosphorus leaching varies according to soil properties (Jarvis, 2007; Liu *et al*., 2012; Jalali & Jalali, 2017) and soil/crop management (McDowell *et al*., 2001; Svanbäck, *et al*., 2014). Consequently, as this farm-scale experiment was implemented in a wide area with a high soil variability, and data was collected from composite samples over plots of ~5ha, it is comprehensible to think about a change zone instead of a change point. According to this, we think that exponential or logarithmic models (Fig. 5.7 B, Fig. 5.7 D) explain satisfactorily that concept of vertical P displacement at local/regional scale.

The reduction of P surplus should be achieved by considering some basic rules such as the use soil tests for keeping P contents at the optimal level, which is to take profit from residual P (Schröder *et al*., 2011), and by matching P crop needs with P inputs (Hooda, 2001). Fortunately, our data show a margin of safety between the agronomic threshold, above which there is no yield response to P (>25 mg/kg, Olsen P), and the environmental change zone, which may cause its vertical displacement (60-80 mg/kg, Olsen P).

5.5 Conclusions

The present study concludes that the mixed crop-livestock systems tended to increase the levels of organic carbon, macronutrients (N, P, and K), and essential oligoelements (Cu, Zn and Mn), while the use of mineral fertilizers seemed to be associated to Cd. The rest of microelements and heavy metals (B, Cr, Co, Fe, Mn, Ni, and Pb) showed no connection with the fertilization practices.

The use of available P appeared to be a useful indicator to characterise the fertilization management from different farming systems, as well as to evaluate the risk of movement of this element from topsoil (0-30 cm) to deeper layers, in calcareous soils, under irrigation. A threshold zone was observed in the range of 60-80 mg P /kg (P-Olsen).

The results of our study are in line with warning threshold of 80 mg/kg (Olsen P) rightly considered by the Ministry of Agriculture in Catalonia as a new measure from its reinforced Nitrates Action Programme following the EU policies, and reinforce the importance of considering residual P in national regulations of Mediterranean areas.

References

Alloway, B. J., & Jackson, A. P. (1991). The behaviour of heavy metals in sewage sludge-amended soils. *Science of The Total Environment*, *100*(C), 151–176. https://doi.org/10.1016/0048-9697(91)90377-Q

Amery, F., & Schoumans, O. F. (2014). *Agricultural phosphorus legislation in Europe. In Ilvo (Issue April). 45p*. https://edepot.wur.nl/300160 ISBN: 9789040303531

Andrades, M.,& Martinez, E. (2022). Fertilidad del suelo y parámetros que la definen. In Universidad de la Rioja (Ed.), *Universidad de la Rioja-Servicio de Publicaciones.* (4th ed., Vol. v3). http://dialnet.unirioja.es/servlet/libro?codigo=267902&info=resumen&idioma=SPA

Ascaso, E., Boixadera, J., & Olarieta, J.R., (1991). Detailed Soil Survey Map of Catalonia of the irrigated area by Algerri-Balaguer Channel (1:25,000). Departament d'Agricultura, Ramaderia i Pesca. Generalitat de Catalunya

Ballabio, C., Panagos, P., Lugato, E., Huang, J.-H., Orgiazzi, A., Jones, A., Fernández-Ugalde, O., Borrelli, P., & Montanarella, L. (2018). Copper distribution in European topsoils: An assessment based on LUCAS soil survey. *Science of The Total Environment*, *636*, 282–298. https://doi.org/10.1016/j.scitotenv.2018.04.268

Barreau, S., Magnier, J., & Alcouffe, C. (2018). *Agricultural phosphorus regulation in Europe-Experience-sharing for 4 European countries International Office for Water. 45p.* https://www.oieau.fr/eaudoc/system/files/34158_0.pdf

Beauchemin, S., Simard, R. R., & Cluis, D. (1998). Forms and Concentration of Phosphorus in Drainage Water of Twenty-Seven Tile-Drained Soils. *Journal of Environmental Quality*, *27*(3), 721–728. https://doi.org/10.2134/JEQ1998.00472425002700030033X

Bennett, E.M., Carpenter, S.R., Caraco, N.F. (2001). Human Impact on Erodable Phosphorus and Eutrophication: A Global Perspective: Increasing accumulation of phosphorus in soil threatens rivers, lakes, and coastal oceans with eutrophication, *BioScience*, *51*(3), 227–234. https://doi.org/10.1641/0006-3568(2001)051[0227:HIOEPA]2.0.CO;2

Berenguer, P., Santiveri, F., Boixadera, J., & Lloveras, J. (2008a). Fertilisation of irrigated maize with pig slurry combined with mineral nitrogen. *European Journal of Agronomy*, *28*(4), 635–645. https://doi.org/10.1016/j.eja.2008.01.010

Berenguer, P., Cela, S., Santiveri, F., Boixadera, J., & Lloveras, J. (2008b). Copper and Zinc Soil Accumulation and Plant Concentration in Irrigated Maize Fertilized with Liquid Swine Manure. *Agronomy Journal*, *100*(4), 1056–1061. https://doi.org/10.2134/agronj2007.0321

Bernhoft, A., Amundsen, C. E., Källqvist, T., Rudi, K., Sogn, T., Yazdankhah, S., & Ørnsrud, R. (2014). *Zinc and copper in pig and poultry production-fate and effects in the food chain and the environament. 128p.*

https://vkm.no/download/18.2994e95b15cc54507161edc3/1501777318338/e06b487e66.pdf ISBN:978-82-8259-093-8

Biau, A., Santiveri, F., & Lloveras, J. (2013). Stover management and nitrogen fertilization effects on corn production. *Agronomy Journal*, *105*(5), 1264–1270. https://doi.org/10.2134/agronj2

BOE (1990). Royal Decree 1310/1990, of October 29, which regulates the use of sewage sludge in the agricultural sector. Boletín Oficial del Estado 262, 01/11/1990, https://www.boe.es/eli/es/rd/1990/10/29/1310 Accessed 21/09/2021

Bomans, E., Fransen, K., Gobin, A., Mertens, J., Michiels, P., Vandendriessche, H., & Vogels, N. (2005). *Addressing phosphorus related problems in farm practice', Final report to the European Commission.* https://ec.europa.eu/environment/natres/pdf/phosphorus/AgriPhosphorusReport%20final.pdf

Bosch-Serra, A. D., Yagüe, M. R., Valdez, A. S., & Domingo-Olivé, F. (2020). Dairy cattle slurry fertilization management in an intensive Mediterranean agricultural system to sustain soil quality while enhancing rapeseed nutritional value. *Journal of Environmental Management*, *273*, 111092. https://doi.org/10.1016/j.jenvman.2020.111092

Carrey, R., Ballesté, E., Blanch, A. R., Lucena, F., Pons, P., López, J. M., Rull, M., Solà, J., Micola, N., Fraile, J., Garrido, T., Munné, A., Soler, A., & Otero, N. (2021). Combining multi-isotopic and molecular source tracking methods to identify nitrate pollution sources in surface and groundwater. *Water Research*, *188*, 116537. https://doi.org/10.1016/j.watres.2020.116537

Cela, S., Berenguer, P., Santiveri, F., & Lloveras, J. (2010). Potential Phosphorus, Potassium, and Magnesium Surpluses in an Irrigated Maize Monoculture Fertilized with Pig Slurry. *Agronomy Journal*, *102*(1), 96–102. https://doi.org/10.2134/agronj2009.0139

Chardon, W. J., Oenema, O., Castilho, P. del, Vriesema, R., Japenga, J., & Blaauw, D. (1997). Organic Phosphorus in Solutions and Leachates from Soils Treated with Animal Slurries. *Journal of Environmental Quality*, *26*(2), 372–378. https://doi.org/10.2134/JEQ1997.00472425002600020006X

Chowdhury, R., & Zhang, X. (2021). Phosphorus use efficiency in agricultural systems: A comprehensive assessment through the review of national scale substance flow analyses. *Ecological Indicators,121*, 107172. https://doi.org/10.1016/j.ecolind.2020.107172

DACC (2022). Departament d'Acció Climàtica, Alimentació i Agenda Rural. Estadístiques definitives de conreus. Gabinet Tècnic. Servei d'Estadística i Preus Agroalimentaris. https://agricultura.gencat.cat/ca/departament/estadistiques/agricultura/estadistiques-definitives-conreus/ Accessed 04/08/2022

de Vries, W., Römkens, P.F.A.M., Kros, J., Voogd, J.C., & Schulte-Uebbing, L.F. (2022). *Impacts of nutrients and heavy metals in European agriculture. Current and critical inputs in relation to air, soil and water quality*. 72p. ETC-DI. https://www.eea.europa.eu/data-and-maps/data/external/impacts-of-nutrients-and-heavy

DOGC. (2019). Decree 153/2019, of 3 July, on the management of the soil fertilisation and manure, and the implementation of the action programme in vulnerable areas to nitrate pollution from agricultural sources. Diari Oficial de la Generalitat de Catalunya (Catalonia) 7911, 05/07/19. https://portaljuridic.gencat.cat/eli/es-ct/d/2019/07/03 Accessed 21/10/2022

Domingo-Olivé, F., Bosch-Serra, À. D., Yagüe, M. R., Poch, R. M., & Boixadera, J. (2016). Long term application of dairy cattle manure and pig slurry to winter cereals improves soil quality. *Nutrient Cycling in Agroecosystems*, *104*(1), 39–51. https://doi.org/10.1007/s10705-015-9757-7

Einarsson, R., Pitulia, D., & Cederberg, C. (2020). Subnational nutrient budgets to monitor environmental risks in EU agriculture: calculating phosphorus budgets for 243 EU28 regions using public data. *Nutrient Cycling in Agroecosystems*, *117*(2), 199–213. https://doi.org/10.1007/s10705-020-10064-y

EU Nitrogen Expert Panel (2015) Nitrogen Use Efficiency (NUE) - an indicator for the utilization of nitrogen in agriculture and food systems. Wageningen University, Alterra, PO Box 47, NL-6700 Wageningen, Netherlands

Eurostat (2021a). Eurostat regional yearbook. 2021 edition. Publications Office of the European Union. Accessed 18/09/2022

Eurostat (2021b). Agricultural nutrients. Gross nutrient balance. Available in https://ec.europa.eu/eurostat/databrowser/view/aei_pr_gnb/default/bar?lang=en Accessed 28/10/2021.

Freiberger, R. P., Heeren, D. M., Fox, G. A., Penn, C. J., & Eisenhauer, D. E. (2014). *Finite element modeling of long-term phosphorus leaching through macropores in the Ozark ecoregion*. 376p. https://digitalcommons.unl.edu/biosysengfacpub/376

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Gómez-Miguel, V. D., & Sotés, V. (2014). *El Manganeso y la Viticultura: una revisión* (A. y M. A. Ministerio de Agricultura (Ed.)). http://publicacionesoficiales.boe.es/

Goss, M. J., Tubeileh, A., & Goorahoo, D. (2013). A Review of the Use of Organic Amendments and the Risk to Human Health. *Advances in Agronomy, 120*, 275-379. https://doi.org/10.1016/B978-0-12-407686-0.00005-1

Heckrath, G., Brookes, P. C., Poulton, P. R., & Goulding, K. W. T. (1995). Phosphorus Leaching from Soils Containing Different Phosphorus Concentrations in the Broadbalk Experiment. *Journal of Environmental Quality*, *24*(5), 904–910. https://doi.org/10.2134/JEQ1995.00472425002400050018X

Herrero, J., Poch, R.M., Porta, J., & Boixadera, J., (1996). Soils with gypsum of the Central Catalan Depression. Excursion Guide: International Symposium on Soils with Gypsum. Edicions Universitat de Lleida. ISBN 84-89727-03-1

Hooda, P. S., Moynagh, M., Svoboda, I. F., Edwards, A. C., Anderson, H. A., & Sym, G. (1999). Phosphorus Loss in Drainflow from Intensively Managed Grassland Soils. *Journal of Environmental Quality*, *28*(4), 1235–1242. https://doi.org/10.2134/JEQ1999.00472425002800040026X

Hooda, P. S., Truesdale, V. W., Edwards, A. C., Withers, P. J. A., Aitken, M. N., Miller, A., & Rendell, A. R. (2001). Manuring and fertilization effects on phosphorus accumulation in soils and potential environmental implications. *Advances in Environmental Research*, *5*(1), 13–21. https://doi.org/10.1016/S1093-0191(00)00037-X

Horn, J.L. (1965). A rationale and test for the number of factors in factor analysis. Psychometrika, 30, 179–185

Hughes, S., Reynolds, B., Bell, S. A., & Gardner, C. (2000). Simple phosphorus saturation index to estimate risk of dissolved P in runoff from arable soils. *Soil Use and Management*, *16*(3), 206–210. https://doi.org/10.1111/J.1475-2743.2000.TB00194.X

Iglesias, M., Marguí, E., Camps, F., & Hidalgo, M. (2018). Extractability and crop transfer of potentially toxic elements from mediterranean agricultural soils following long-term sewage sludge applications as a fertilizer replacement to barley and maize crops. *Waste Management*, *75*, 312–318. https://doi.org/10.1016/j.wasman.2018.01.024

Jalali, M. (2007). Phosphorus status and sorption characteristics of some calcareous soils of Hamadan, western Iran. *Environmental Geology 2007 53:2*, *53*(2), 365–374. https://doi.org/10.1007/S00254-007-0652-7

Jalali, M., & Jalali, M. (2017). Assessment risk of phosphorus leaching from calcareous soils using soil test phosphorus. *Chemosphere*, *171*, 106–117. https://doi.org/10.1016/j.chemosphere.2016.12.042

James, D. W., Kotuby-Amacher, J., Anderson, G. L., & Huber, D. A. (1996). Phosphorus Mobility in Calcareous Soils under Heavy Manuring. *Journal of Environmental Quality*, *25*(4), 770–775. https://doi.org/10.2134/JEQ1996.00472425002500040017X

Jarvis, N. J. (2007). A review of non-equilibrium water flow and solute transport in soil macropores: principles, controlling factors and consequences for water quality. *European Journal of Soil Science*, *58*(3), 523–546. https://doi.org/10.1111/j.1365-2389.2007.00915.x

Johnston, A. E., & Poulton, P. R. (2019). Phosphorus in Agriculture: A Review of Results from 175 Years of Research at Rothamsted, UK. *Journal of Environmental Quality*, *48*(5), 1133–1144. https://doi.org/10.2134/jeq2019.02.0078

Jolliffe, I. (2002). *Jolliffe, I. (2002) Principal Component Analysis. 2nd Edition, Springer, New York. - References - Scientific Research Publishing* (Second). https://www.scirp.org/(S(i43dyn45teexjx4

Kerkaert, H. R., Woodworth, J. C., DeRouchey, J. M., Dritz, S. S., Tokach, M. D., Goodband, R. D., & Manzke, N. E. (2021). Determining the effects of manganese source and level on growth performance and carcass characteristics of growing–finishing pigs. *Translational Animal Science*, *5*(2). https://doi.org/10.1093/tas/txab067

Kubier, A., Wilkin, R. T., & Pichler, T. (2019). Cadmium in soils and groundwater: A review. *Applied Geochemistry*, *108*, 104388. https://doi.org/10.1016/j.apgeochem.2019.104388

Liu, J., Aronsson, H., Bergström, L., & Sharpley, A. (2012). Phosphorus leaching from loamy sand and clay loam topsoils after application of pig slurry. *SpringerPlus*, *1*(1), 1–10. https://doi.org/10.1186/2193-1801-1-53/FIGURES/1

Logan, T. J., & McLean, E. O. (1973). Effects of Phosphorus Application Rate, Soil Properties, and Leaching Mode on 32P Movement in Soil Columns. *Soil Science Society of America Journal*, *37*(3), 371–374. https://doi.org/10.2136/SSSAJ1973.03615995003700030018X

López Arias, M., & Grau Corbí, J. M. (2004). *Metales pesados, materia orgánica y otros parámetros de la capa superficial de los suelos agrícolas y de pastos de la España Peninsular I: resultados globales.* (Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA) (Ed.)). Ministerio de Medio Ambiente. Gobierno de España

Maguire, R. O., & Sims, J. T. (2002). Soil testing to predict phosphorus leaching. *Journal of Environmental Quality*, *31*(5), 1601–1609. https://doi.org/10.2134/JEQ2002.1601

Mantovi, P., Bonazzi, G., Maestri, E., & Marmiroli, N. (2003). Accumulation of copper and zinc from liquid manure in agricultural soils and crop plants. *Plant and Soil 2003 250:2*, *250*(2), 249–257. https://doi.org/10.1023/A:1022848131043

MAPAMA (2018). Balance del fósforo 2016: metodología y resultados. Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente. Gobierno de España. https://www.mapa.gob.es/es/agricultura/temas/medios-de-produccion/productos-fertilizantes/ Accessed 17/03/2021

Martínez, E., Domingo, F., Roselló, A., Serra, J., Boixadera, J., & Lloveras, J. (2017). The effects of dairy cattle manure and mineral N fertilizer on irrigated maize and soil N and organic C. *European Journal of Agronomy*, *83*, 78–85. https://doi.org/10.1016/j.eja.2016.10.002

Martínez, E., Maresma, A., Biau, A., Berenguer, P., Cela, S., Santiveri, F., Michelena, A., & Lloveras, J. (2020). Long-term effects of liquid swine manure on soil organic carbon and Cu/Zn levels in soil and maize. *Nutrient Cycling in Agroecosystems*, *118*(2), 193–205. https://doi.org/10.1007/s10705-020-10093-7

McDowell, R. W., & Sharpley, A. N. (2001). Phosphorus losses in subsurface flow before and after manure application to intensively farmed land. *The Science of the Total Environment*, *278*(1–3), 113–125. https://doi.org/10.1016/S0048-9697(00)00891-3

McDowell, R., Sharpley, A., Brookes, P., & Poulton, P. (2001). Relationship between soil test phosphorus and phosphorus release to solution. *Soil Science*, *166*(2), 137–149. https://doi.org/10.1097/00010694-200102000-00007

Millaleo, R., Reyes-Díaz, M., Ivanov, A. G., Mora, M. L., & Alberdi, M. (2010). Manganese as essential and toxic element for plants: transport, accumulation and resistance mechanisms. *Journal of Soil Science and Plant Nutrition*, *10*(4), 470–481. https://doi.org/10.4067/S0718-95162010000200008

Mousavi, S. R., Galavi, M., & Rezaei, M. (2013). Zinc (Zn) Importance for Crop Production - A Review. *Undefined*

Norwegian Food Authority. (2014). *Zinc and Copper in Pig and Poultry Production—Fate and Effects in the Food Chain and the Environment*. 128p. https://vkm.no/english/riskassessments/allpublications/zincandco

Novak, L. T., Adriano, D. C., Coulman, G. A., & Shah, D. B. (1975). Phosphorus Movement in Soils: Theoretical Aspects. *Journal of Environmental Quality*, *4*(1), 93–99. https://doi.org/10.2134/JEQ1975.00472425000400010021X

OJ (1986). Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture. Official Journal L 181, 04/07/1986. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:31986L0278&from=EN Accessed 21/09/2021.

OJ (1991). Council Directive 91/676/EEC of 12 December 1991 oncerning the protection of waters against pollution caused by nitrates from agricultural sources. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:31991L0676&from=EN Accessed 21/09/2021.

OJ (2019). Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003. http://data.europa.eu/eli/reg/2019/1009/oj Accessed 02/10/2022

Ovejero, J., Ortiz, C., Boixadera, J., Serra, X., Ponsá, S., Lloveras, J., & Casas, C. (2016). Pig slurry fertilization in a double-annual cropping forage system under sub-humid Mediterranean conditions. *European Journal of Agronomy*, *81*, 138–149. https://doi.org/10.1016/j.eja.2016.09.005

Peres-Neto, P. R., Jackson, D. A., & Somers, K. M. (2005). How many principal components? stopping rules for determining the number of non-trivial axes revisited. *Computational Statistics & Data Analysis*, *49*(4), 974–997. https://doi.org/10.1016/J.CSDA.2004.06.015

Perramon, B., Domingo-Olivé, F., Bosch-Serra, Á. D., Yagüe, M. R., & Boixadera, J. (2018). Double-Annual Forage Crop Rotation Controls Nutrient Surpluses in Nitrogen-Based Organic Fertilization. *Agronomy Journal*, *110*(6), 2268–2276. https://doi.org/10.2134/agronj2018.02.0099

Peyraud, J., & MacLeod, M. (2020). *Future of EU livestock - Publications Office of the EU*. https://doi.org/10.2762/3440

Pote, D. H., Daniel, T. C., Moore, P. A., Nichols, D. J., Sharpley, A. N., & Edwards, D. R. (1996). Relating Extractable Soil Phosphorus to Phosphorus Losses in Runoff. *Soil Science Society of America Journal* *60*(3), 855–859. https://doi.org/10.2136/sssaj1996.03615995006000030025x

Poulsen, H. (1998). Zinc and copper as feed additives, growth factors or unwanted environmental factors. *Journal of Animal and Feed Sciences*, *7*(Suppl. 1), 135–142. https://doi.org/10.22358/jafs

Powlson, D. S., Bhogal, A., Chambers, B. J., Coleman, K., Macdonald, A. J., Goulding, K. W. T., & Whitmore, A. P. (2012). The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: A case study. *Agriculture, Ecosystems & Environment*, *146*(1), 23–33. https://doi.org/10.1016/j.agee.2011.10.004

Renneson, M., Barbieux, S., & Colinet, G. (2016). Indicators of phosphorus status in soils: significance and relevance for crop soils in southern Belgium. A review. *Base*, *20*(S1), 257–272. https://doi.org/10.25518/1780-4507.13021

Risberg, K., Cederlund, H., Pell, M., Arthurson, V., & Schnürer, A. (2017). Comparative characterization of digestate versus pig slurry and cow manure – Chemical composition and effects on soil microbial activity. *Waste Management*, *61*, 529–538. https://doi.org/10.1016/j.wasman.2016.12.016

Robbins, C. W., & Smith, J. H. (1977). Phosphorus Movement in Calcareous Soils Irrigated with Waste Water from Potato Processing Plants. *Journal of Environmental Quality*, *6*(2), 222–225. https://doi.org/10.2134/JEQ1977.00472425000600020025X

Rodríguez-Martín, J.A., López-Arias, M., Grau-Corbí, J. M. (2009). *Metales Pesados , Materia Orgánica y otros Parámetros de los Suelos Agrícolas y Pastos de España*. 225 p. Ministerio de Medio Ambiente Y Medio Rural Y Marino (Ed.)

Römkens, P.F.A.M., Rietra, R.P.J.J., Kros, J., Voogd, J.C., & de Vries, W., (2018). *Impact of cadmium levels in fertilisers on cadmium accumulation in soil and uptake by food crops*. 115p. Wageningen, the Netherlands: Wageningen Environmental Research. https://edepot.wur.nl/451353

Rosemarin, A., Ekane, N., & Andersson, K. (2021). Phosphorus Flows, Surpluses, and N/P Agronomic Balancing When Using Manure from Pig and Poultry Farms. *Agronomy*, *11*(11), 2228. https://doi.org/10.3390/agronomy11112228

Roswall, T., Lucas, E., Yang, Y.-Y., Burgis, C., Scott, I., & Toor, G. (2021). Hotspots of Legacy Phosphorus in Agricultural Landscapes: Revisiting Water-Extractable Phosphorus Pools in Soils. *Water*, *13*(8), 1006. https://doi.org/10.3390/w13081006

Schoumans, O. F., Bouraoui, F., Kabbe, C., Oenema, O., & van Dijk, K. C. (2015). Phosphorus management in Europe in a changing world. *AMBIO*, *44*(S2), 180–192. https://doi.org/10.1007/s13280-014-0613-9

Schröder, J. J., Cordell, D., Smit, A. L., & Rosemarin, A. (2010). Sustainable use of phosphorus. 124p. Wageningen: Plant Research International. Report 357. https://edepot.wur.nl/163942

Schröder, J. J., Smit, A. L., Cordell, D., & Rosemarin, A. (2011). Improved phosphorus use efficiency in agriculture: A key requirement for its sustainable use. *Chemosphere*, *84*(6), 822–831. https://doi.org/10.1016/j.chemosphere.2011.01.065

Sharpley, A.N., & Halvorson, A.D., (1994). The management of soil phosphorus availability and its impact on surface water quality. In: Lal R, Stewart BA, editors. Soil processes and water quality. Boca Raton, FL: Lewis, Publishers. 1994, 7–90

Sharpley, A., Daniel, T. C., Sims, J. T., & Pote, D. H. (1996). Determining environmentally sound soil phosphorus levels. *Journal of Soil and Water Conservation*, *51*(2), 160–166. https://www.jswconline.org/content/51/2/160

Sims, J. T., Simard, R. R., & Joern, B. C. (1998). Phosphorus Loss in Agricultural Drainage: Historical Perspective and Current Research. *Journal of Environmental Quality*, *27*(2), 277–293. https://doi.org/10.2134/JEQ1998.00472425002700020006X

Soil Survey Staff (2014). Keys to Soil Taxonomy. USDA-Natural Resources Conservation 556 Service, Washington D.C

Stamm, C., Binder, C. R., Frossard, E., Haygarth, P. M., Oberson, A., Richardson, A. E., Schaum, C., Schoumans, O., & Udert, K. M. (2022). Towards circular phosphorus: The need of inter- and transdisciplinary research to close the broken cycle. *Ambio*, *51*(3), 611–622. https://doi.org/10.1007/s13280-021-01562-6

Svanbäck, A., Ulén, B., & Etana, A. (2014). Mitigation of phosphorus leaching losses via subsurface drains from a cracking marine clay soil. *Agriculture, Ecosystems & Environment*, *184*, 124–134. https://doi.org/10.1016/j.agee.2013.11.017

Tóth, G., Guicharnaud, R.-A., Tóth, B., & Hermann, T. (2014). Phosphorus levels in croplands of the European Union with implications for P fertilizer use. *European Journal of Agronomy*, *55*, 42–52. https://doi.org/10.1016/j.eja.2013.12.008

Valdez, A. S., Bosch-Serra, À. D., Yagüe, M. R., Poch, R. M., & Puigpinós, E. (2020). Earthworm community and soil microstructure changes with long-term organic fertilization. *Archives of Agronomy and Soil Science*, *66*(7), 957–970. https://doi.org/10.1080/03650340.2019.1648792

Walkley A, Black IA, 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil science, 37(1), 29–38

Wang, Y. T., Zhang, T. Q., Hu, Q. C., Tan, C. S., Halloran, I. P. O., Drury, C. F., Reid, D. K., Ma, B. L., Ball-Coelho, B., Lauzon, J. D., Reynolds, W. D., & Welacky, T. (2010). Estimating Dissolved Reactive Phosphorus Concentration in Surface Runoff Water from Major Ontario Soils. *Journal of Environmental Quality*, *39*(5), 1771–1781. https://doi.org/10.2134/jeq2009.0504

Webb, J., Sorensen, P., Velthof, G. L., Amon, B., Pinto, M., Rodhe, L., Salomon, E., Hutchings, N., Burczyk, J., & Reid, J. E. (2011). Study on variation of manure N efficiency throughout Europe. (Final report). AEA Technology plc. http://ec.europa.eu/environment/water/water-nitrates/pdf/Man_N_Eff_Final%20Report.pdf Accessed 21/01/2015

Xu, Y., Yu, W., Ma, Q., & Zhou, H. (2013). Accumulation of copper and zinc in soil and plant within ten-year application of different pig manure rates. *Plant, Soil and Environment*, *59*(No. 11), 492–499. https://doi.org/10.17221/121/2013-PSE

Yagüe, M. R., & Quílez, D. (2013). Residual Effects of Fertilization with Pig Slurry: Double Cropping and Soil. *Agronomy Journal*, *105*(1), 70–78. https://doi.org/10.2134/agronj2012.0191

Yagüe, M. R., Bosch-Serra, À. D., Antúnez, M., & Boixadera, J. (2012). Pig slurry and mineral fertilization strategies' effects on soil quality: Macroaggregate stability and organic matter fractions. *Science of The Total Environment*, *438*, 218–224. https://doi.org/10.1016/j.scitotenv.2012.08.063

Yagüe, M. R., Domingo-Olivé, F., Bosch-Serra, À. D., Poch, R. M., & Boixadera, J. (2016). Dairy Cattle Manure Effects on Soil Quality: Porosity, Earthworms, Aggregates and Soil Organic Carbon Fractions. *Land Degradation & Development*, *27*(7), 1753–1762. https://doi.org/10.1002/ldr.2477

Zaragüeta, A., Enrique, A., Virto, I., Antón, R., Urmeneta, H., & Orcaray, L. (2021). Effect of the Long-Term Application of Sewage Sludge to A Calcareous Soil on Its Total and Bioavailable Content in Trace Elements, and Their Transfer to the Crop. *Minerals*, *11*(4), 356. https://doi.org/10.3390/min11040356

Capítol 6. Discussió i conclusions generals

6.1 Discussió general

El maneig de la fertilització dels cultius extensius a Catalunya és una tasca complexa, on part de la dificultat ve donada per la gran variabiabilitat pluviomètrica i la disponibilitat d'aigua que es donen en els diferents sistemes agrícoles mediterranis. Però la resposta encara es complica més quan es fa referència a l'ús de les dejeccions ramaderes i a altres fertilitzants orgànics, degut a la seua composició, així com al comportament dels elements que contenen un cop s'han aplicat als sòls agrícoles.

En els sistemes agrícoles de secà el principal repte, molt probablement, hauria de consistir en la reducció substancial de les aportacions de N sense comprometre les produccions. Els secans semiàrids estudiats (pluviometria mitjana ~400 mm, elevada ETo de >1000 mm/any i temperatures altes en les darreres etapes del cicle dels cultius, ~20 ºC), tenen el potencial productiu condicionat a la pluviometria. Durant el període d'estudi (2003-2016), es van enregistrar entre 201 i 621 mm, també amb gran variabilitat observada (dels 8 als 100 mm) en períodes crítics per al desenvolupament de la planta, com l'etapa d'elongació de la tija (Blum, 1998; Ryan et al., 2009). Conseqüentment, el ventall de cultius que tenen possibilitats de desenvolupar-se a la zona es redueix a l'ordi, principalment, alternat molt esporàdicament amb blat, colza i anys de guaret. Els rendiments mitjans dels anys considerats secs, que van ser 8 de 13, deixant de banda un any humid en què la pedra va malmetre la collita, s'han situat entorn dels 2500, 2000 i 1900 kg/ha en ordi, blat i colza, respectivament, mentre que els pocs anys més humits s'ha arribat als 4000 i 4600 kg/ha en ordi i blat, respectivament.

En aquestes condicions, la resposta a la fertilització nitrogenada és, en general, molt baixa o, fins i tot, inexistent, de tal manera que només en comptades ocasions hi ha un efecte del N en els rendiments. La colza presenta bona resposta al N quan el cultiu anterior té elevades extraccions. D'altra banda, les aplicacions continuades de fertilitzants donen lloc a un N residual també descrit per altres autors (Daudén et al., 2004; Cela et al., 2011; Yagüe & Quílez, 2013) que s'acumula al sòl, atesa la incapacitat del cultiu d'aprofitar-lo i la poca probabilitat de perdre's per rentat (Angás et al., 2006; Fan et al., 2010). Aquest N romanent, s'aprofita en alguns anys de més pluviometria i pot, ocasionalment, originar resposta a l'adobatge. S'ha observat aquest fet més aviat en blat que no en ordi.

En l'escenari estudiat, es poden plantejar diverses recomanacions per encarar la fertilització dels cultius extensius d'hivern: l'aplicació de purí de porc o llots de depuradora abans de la sembra, malgrat que la seva aplicació continuada tendeix a acumular N al sòl; l'aportació d'adob mineral amb N a cobertera (50 kg N/ha), sent una solució interessant en zones de baixa disponibilitat d'esmenes orgàniques; la no aportació de N, és l'alternativa menys costosa i de menor impacte ambiental, però una opció no sostenible per la mineria de recursos a llarg termini (García-Serrano et al., 2010; Blum, 2013). Per tot això, cal enfocar la fertilització de manera més integral, tot considerant els objectius productius que garanteixin bons rendiments en anys plujosos, però també els mediambientals, és a dir, tenint en compte la reposició de nutrients i minimitzant l'acumulació de N residual al sòl.

Quan passem a un sistema productiu amb una mica més de disponibilitat d'aigua (~450 mm), les produccions mitjanes s'incrementen per un factor d'1,4 i també ho fan, tot i que en menor mesura (factor d'1,1), les exportacions de N. Aquest fet comporta que, en certs casos, malgrat hi hagi una major pluviometria, es continuï aplicant N per sobre de les necessitats dels cultius.

No obstant això, aquesta major disponibilitat d'aigua ofereix l'oportunitat d'incorporar alternatives per mirar d'aprofitar millor les aportacions de N.

Una part fonamental per garantir la sostenibilitat quant al maneig dels sòls i la fertilització resideix en l'aprofitament dels nutrients. El concepte d'eficiència del N s'ha avaluat per molts autors en base a multitud d'índex diferents (López-Bellido et al., 2006; Johnston & Poulton, 2009; Webb et al., 2011; Bosch-Serra et al., 2015), però destaca el NUE (EU Expert N Panel, 2015) per ser una eina senzilla que ha permès identificar quines estratègies estudiades han estat més eficients. En secans semiàrids, els valors de NUE més elevats (61 %) els hem obtingut amb la dosi més baixa de purins (171 kg N/ha) i considerant l'any de guaret en l'interval considerat. La baixa disponibilitat d'aigua condiciona les extraccions de N, tot incidint en l'índex NUE si no es redueixen les aportacions de N (Quemada & Gabriel, 2016). La no consideració del període de guaret reduïa l'índex al 40 %.

En aquest sentit, considerar l'efecte residual dels fertilitzants orgànics és una clara mesura d'eficiència en ajudar a reduir les futures aportacions de N, cosa que el fa una peça fonamental a tenir en compte en la planificació de la fertilització. Ara bé, desestimar-lo, en farà incrementar el seu contingut i, amb ell, els riscos de pèrdua per rentat. En l'experiment ubicat en una zona de secà subhumit, l'efecte residual del sumatori dels 3 anys posteriors a aplicacions puntuals de purins porcins se situa al voltant del 22 i 23 % del N aportat, que equival al 89 i 90 % del N orgànic, calculat en base al rendiment i al N extret, respectivament. Aquest N recuperat prové de la part orgànica, però també de la part mineral aplicada i no absorbida, la qual torna a ser disponible en moments amb nova disponibilitat d'aigua, tal i com apunta Bosch-Serra (2010). Per tant, es recalca la importància de considerar aquest N romanent i la necessitat de monitoritzar els sòls, especialment després d'anys secs o males collites.

Una altra mesura estudiada per mirar de reduir les aportacions de N i, incrementar l'eficiència del sistema, consisteix en introduir nous cultius en la rotació per tal de fer-ne un millor aprofitament sense repercutir en la producció. Novament, la dependència de l'aigua és decisiva en els rendiments dels cultius implementats en la rotació, destacant especialment la mala adaptació del pèsol en anys secs (Xiao et al., 2009; Dogan et al., 2015), cosa que té un impacte productiu negatiu en el conjunt de la rotació. Igualment, la colza no va funcionar tant bé com l'ordi durant el període sec, en part per una millor eficiència de l'aigua del segon (Sadras & McDonald, 2011). Pel que fa a les extraccions de les dues tipologies de rotacions implementades, la rotació ordi-colza és la que ha extret més N, tenint en compte que venia d'un any de guaret. En la segona seqüència de rotacions, l'ordre ordi-pèsol ha resultat ser la millor opció, considerant que el pèsol està molt condicionat per la manca d'aigua. La introducció de lleguminoses i crucíferes en les rotacions de cereals d'hivern, juntament amb períodes de guaret, comporta un conjunt de beneficis ambientals, però alhora pot comprometre les produccions, cosa que fa necessari que aquest risc continuï sent compensat per les polítiques europees actuals (COM 2018; CE, 2022).

Si ens centrem en els sistemes agraris de regadiu, on la pluviometria (~400 mm) es complementa amb reg a pressió (600 mm), l'elevada disponibilitat d'aigua juntament amb un major control de la mateixa, condueixen a la possibilitat d'incrementar substancialment les produccions, ampliar el ventall de cultius i arribar a incloure dos cultius en un mateix any (Maresma et al., 2018; Maresma et al., 2019; Malik & Dechmi, 2020). En aquest escenari, s'acostuma a fer una fertilització més intensiva (Cavero, et al., 2003; Sisquella et al., 2004;

Isidoro et al., 2006), sobretot en els cereals d'estiu com el blat de moro, atés que no l'excés de nutrients no té un efecte notori en el rendiment, tal i com ocorreria en l'ordi amb l'ajagut (Telkar et al., 2012; Dahiya et al., 2018). Malgrat que les extraccions del cultiu poden arribar a triplicar els valors de zones de secà (Yagüe & Quílez, 2010; Cela et al., 2011), el risc d'acumulació de N residual (Martínez et al., 2017) i altres elements (Berenguer et al., 2008) deguda a les aplicacions intensives, ha de tenir-se en consideració per no malmetre la qualitat dels sòls i de les aigües (Peyraud & MacLeod, 2020).

L'estudi efectuat sobre més de 700 ha de cultius extensius en regadiu va identificar una gran variabilitat en els continguts de determinats elements dels sòls, indicant una forta relació d'alguns d'ells (matèria orgànica, P i K assimilables) amb el maneig de la fertilització. En molts casos, s'ha observat un desequilibri amb parcel·les amb excés de macronutrients (P i K assimilables), amb valors per sobre dels nivells de recomanació dels cultius (Andrades & Martínez, 2022), però, sorprenentment, també s'ha identificat entre un 20 i un 30 % de parcel·les amb deficiències que podrien tenir efectes negatius en els rendiments. Altres paràmetres com el pH, el carbonat càlcic equivalent o la conductivitat eléctrica (1:5) no s'han vist influenciats per les pràctiques de nutrició dels cultius. També s'ha detectat una forta correlació entre l'aportació d'esmenes orgàniques i els continguts d'oligoelements com ara el Cu, Zn i Mn (extracció amb DTPA) i Cu i Zn totals (extracció àcida), cosa que suposa un benefici de cara a nodrir els sòls amb aquests microelements essencials, però, alhora, un avís, en tant que concentracions elevades poden incidir negativament sobre la salut del sòl. Per contra, la utilització d'adobs minerals alerta sobre una potencial acumulació de Cd, un tema que està prenent cada cop més importància (Römkens et al., 2018) i que, fins i tot, s'ha inclòs en la recent normativa comunitària en materia de fertilitzants (OJ, 2019). Finalment, la resta de microelements i metalls pesants analitzats (B, Cr, Co, Fe, Mn, Ni i Pb) no han estat associats a les pràctiques de fertilització i es relacionen, més probablement, amb la gènesi dels sòls, tal i com apunten autors com Bosch-Serra et al. (2020).

Quan l'acumulació residual de P al sòl, com a conseqüència de l'aplicació continuada d'esmenes orgàniques, arriba a nivells crítics situats entre 60 i 80 mg/kg (P Olsen) es dona un desplaçament vertical d'aquest element cap a capes més profundes. Aquest moviment probablement es relaciona amb el límit de retenció de P d'aquests sòls, fet que el movilitza el P orgànic soluble a través dels macropurus (Jarvis, 2007; Freiberger *et al*., 2014) per via de la matèria orgànica dissolta o de partícules col·loidals (James *et al*., 1996; Chardon *et al*., 1997). Aquesta "zona de canvi" representa un risc de pèrdua d'aquest nutrient en sòls calcaris, especialment rellevant si són poc profunds o tenen el nivell freàtic proper a la superfície. No obstant això, en les nostres condicions, hi ha un cert marge de seguretat entre els llindars agronòmics que indiquen la no resposta a la fertilització fosfatada i aquesta zona de canvi.

6.2 Conclusions generals

La resposta a la fertilització nitrogenada en els secans semiàrids ha estat, en general, molt baixa o, fins i tot, inexistent, de tal manera que només en comptades ocasions hi ha un efecte positiu del N en els rendiments. Tanmateix, sota una visió més holística de la fertilització, per garantir els rendiments en anys plujosos, fer una reposició de nutrients, minimitzar l'acumulació de N residual i contribuir a l’economia circular, caldria considerar una estratègia basada en l’aportació d’adobs orgànics en anys alterns.

L’eficiència en l’ús del N (NUE) amb les aportacions de purins de porc se situa entorn del 60 %, tant en els secans semiàrids com en els secans subhumits d’aquest estudi. Les aportacions de N en cobertora (50 kg N/ha) redueixen a la meitat el seu valor.

L’efecte residual del N procedent d’aplicacions puntuals de purins ha resultat ser del 22 i 23 % del N aportat, que equival al 89 i 90 % del N orgànic, calculat en base al rendiment i al N extret, respectivament. Aquest N recuperat prové de la part orgànica, però també de la part mineral aplicada i no absorbida, la qual torna a ser disponible en moments amb disponibilitat d’aigua. Es recalca la importància de considerar aquest N romanent i la necessitat de monitoritzar els sòls, especialment després d’anys secs, males collites i després de guarets.

La introducció de colza i pèsol en la rotació amb el monocultiu d’ordi han tingut una pitjor adaptació en relació amb l’ordi durant els anys de baixa disponibilitat d’aigua. La introducció d’ordi com a primer cultiu després de guaret ha donat millors resultats en termes de biomassa total, N extret i producció. Aquesta seqüència de cultius va obtenir els millors rendiments sense l’aplicació de N. La rotació ordi-pèsol va resultar millor que la de pèsol-ordi en termes de N extret i producció, però ha necessitat una aportació suplementària anual de 60 kg N/ha o puntual >125 kg N/ha de purí de porcí a la cobertora de l’ordi.

Els sòls de la zona de regadiu tenen una gran variabilitat pel que fa als paràmetres analitzats, on la matèria orgànica i el P i K assimilables estan fortament relacionats amb el maneig de la fertilització. Hi ha un gran desequilibri quant al contingut de P i K assimilables dels sòls estudiats, amb un 24 i un 39 % de les parcel·les dins el rang òptim, respectivament. S’ha detectat una forta correlació entre l’aportació d’esmenes orgàniques i els continguts d’oligoelements com ara el Cu, Zn i Mn (extracció amb DTPA) i Cu i Zn totals (extracció àcida). L’ús d’adobs minerals indica una potencial acumulació de Cd als sòls estudiats. L’acumulació residual de P al sòl a partir de nivells que oscil·len entre 60 i 80 mg/kg (P Olsen) dona lloc a un desplaçament vertical d’aquest element en profunditat.

Referències

Andrades, Marisol; Martinez, E. (2022). Fertilidad del suelo y parámetros que la definen. In U. de la Rioja (Ed.), *Universidad de la Rioja-Servicio de Publicaciones*. (4a Edición, Vol. v3). http://dialnet.unirioja.es/servlet/libro?codigo=267902&info=resumen&idioma=SPA

Angás, P., Lampurlanés, J., & Cantero-Martínez, C. (2006). Tillage and N fertilization. *Soil and Tillage Research*, *87*(1), 59–71. https://doi.org/10.1016/j.still.2005.02.036

Berenguer, P., Cela, S., Santiveri, F., Boixadera, J., & Lloveras, J. (2008). Copper and Zinc Soil Accumulation and Plant Concentration in Irrigated Maize Fertilized with Liquid Swine Manure. *Agronomy Journal*, *100*(4), 1056–1061. https://doi.org/10.2134/agronj2007.0321

Blum, A. (1998). Improving wheat grain filling under stress by stem reserve mobilisation. *Euphytica 1998 100:1*, *100*(1), 77–83. https://doi.org/10.1023/A:1018303922482

Blum, W. E. H. (2013). Soil and Land Resources for Agricultural Production: General Trends and Future Scenarios-A Worldwide Perspective. *International Soil and Water Conservation Research*, *1*(3), 1–14. https://doi.org/10.1016/S2095-6339(15)30026-5

Bosch-Serra, A.D. (2010). Nitrogen use efficiency in rainfed Mediterranean agriculture. *Encyclopedia of Soil Science*, *1*(1), 1–6. Taylor and Francis. https://doi.org/10.1081/E-ESS-120044989

Bosch-Serra, A. D., Ortiz, C., Yagüe, M. R., & Boixadera, J. (2015). Strategies to optimize nitrogen efficiency when fertilizing with pig slurries in dryland agricultural systems. *European Journal of Agronomy*, *67*, 27–36. https://doi.org/10.1016/j.eja.2015.03.003

Bosch-Serra, A. D., Yagüe, M. R., Valdez, A. S., & Domingo-Olivé, F. (2020). Dairy cattle slurry fertilization management in an intensive Mediterranean agricultural system to sustain soil quality while enhancing rapeseed nutritional value. *Journal of Environmental Management*, *273*, 111092. https://doi.org/10.1016/j.jenvman.2020.111092

Cavero, J., Beltrán, A., & Aragüés, R. (2003). Nitrate exported in drainage waters of two sprinkler-irrigated watersheds. *Journal of Environmental Quality*, *32*(3), 916–926. https://doi.org/10.2134/jeq2003.9160

CE (2022). Decisión de Ejecución de la Comisión de 31.8.2022 por la que se aprueba el plan estratégico de la PAC 2023-2027 de España para la ayuda de la Unión financiada por el Fondo Europeo Agrícola de Garantía y el Fondo Europeo Agrícola de Desarrollo Rural CCI: 2023ES06AFSP001. Accés 19/11/2022

Cela, S., Santiveri, F., & Lloveras, J. (2011). Residual effects of pig slurry and mineral nitrogen fertilizer on irrigated wheat. *European Journal of Agronomy*, *34*(4), 257–262. https://doi.org/10.1016/j.eja.2011.02.003

Chardon, W. J., Oenema, O., Castilho, P., Vriesema, R., Japenga, J., & Blaauw, D. (1997). Organic Phosphorus in Solutions and Leachates from Soils Treated with Animal Slurries.

Journal of Environmental Quality, *26*(2), 372–378. https://doi.org/10.2134/jeq1997.00472425002600020006x

COM (2018). Proposal for a regulation of the European Parliament and of the Council establishing rules on support for strategic plans to be drawn up by member states under the Common agricultural policy (CAP Strategic Plans) and financed by the European Agricultural Guarantee Fund (EAGF) and by the European Agricultural Fund for Rural Development (EAFRD) and repealing Regulation (EU) No 1305/2013 of the European Parliament and of the Council and Regulation (EU) No 1307/2013 of the European Parliament and of the Council. EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2018:392:FIN Accés 30/06/2022

Dahiya, S., Kumar, S., & Chaudhary, C. (2018). Lodging: Significance and preventive measures for increasing crop production. *700. International Journal of Chemical Studies*, *6*(1), 700–705

Daudén, A., Quílez, D., & Martínez, C. (2004). Residual effects of pig slurry applied to a Mediterranean soil on yield and N uptake of a subsequent wheat crop. *Soil Use and Management*, *20*(2), 156–162. https://doi.org/10.1079/SUM2003230

Dogan, E., Rat, I., Kahraman, A., & Ipek, I.S. (2015). Green pea response to deficit irrigation rates under semi-arid climatic conditions. *Bulgarian Journal of Agricultural Science, 21*(5), 1005–1011. http://www.agrojournal.org/21/05-13.pdf

EU Nitrogen Expert Panel (2015). Nitrogen Use Efficiency (NUE) - an indicator for the utilization of nitrogen in agriculture and food systems. Wageningen University, Alterra, PO Box 47, NL-6700 Wageningen, Netherlands

Fan, J., Hao, M., & Malhi, S. S. (2011). Accumulation of nitrate N in the soil profile and its implications for the environment under dryland agriculture in northern China: A review. *Canadian Journal of Soil Science*, *90*(3), 429–440. https://doi.org/10.4141/CJSS09105

Freiberger, R. P., Heeren, D. M., Fox, G. A., Penn, C. J., & Eisenhauer, D. E. (2014). *Finite element modeling of long-term phosphorus leaching through macropores in the Ozark ecoregion*. 376p. https://digitalcommons.unl.edu/biosysengfacpub/376

Garcia-Serrano, P., Ruano, S., Lucena, J.J., & Nogales, M. (2010). Guía pràctica de la fertilización racional de los cultivos en España. Parte I. Ed. Ministerio de Medio Ambiente y Medio Rural y Marino. ISBN: 978-84-491-0997-3 https://www.mapa.gob.es/es/agricultura/publicaciones/Publicaciones-fertilizantes.aspx

Isidoro, D., Quílez, D., & Aragüés, R. (2006). Environmental Impact of Irrigation in La Violada District (Spain). *Journal of Environmental Quality*, *35*(3), 776–785. https://doi.org/10.2134/jeq2005.0065

James, D. W., Kotuby-Amacher, J., Anderson, G. L., & Huber, D. A. (1996). Phosphorus Mobility in Calcareous Soils under Heavy Manuring. *Journal of Environmental Quality*, *25*(4), 770–775. https://doi.org/10.2134/jeq1996.00472425002500040017x

Jarvis, N. J. (2007). A review of non-equilibrium water flow and solute transport in soil macropores: principles, controlling factors and consequences for water quality. *European Journal of Soil Science*, *58*(3), 523–546. https://doi.org/10.1111/j.1365-2389.2007.00915.x

Johnston, A. E., & Poulton, P. R. (2009). Nitrogen in agriculture: an overview and definitions of nitrogen use efficiency. *International Fertiliser Society, 651*. Soil Science Department, Rothamsted Research, Harpenden, Herts. AL5 2JQ, UK. ISBN:978-0-85310-288-5

Johnston, A. E., & Poulton, P. R. (2019). Phosphorus in Agriculture: A Review of Results from 175 Years of Research at Rothamsted, UK. *Journal of Environmental Quality*, *48*(5), 1133–1144. https://doi.org/10.2134/jeq2019.02.0078

López-Bellido, L., López-Bellido, R. J., & López-Bellido, F. J. (2006). Fertilizer Nitrogen Efficiency in Durum Wheat under Rainfed Mediterranean Conditions: Effect of Split Application. *Agronomy Journal*, *98*(1), 55–62. https://doi.org/10.2134/AGRONJ2005.0017

Malik, W., & Dechmi, F. (2020). Modelling agricultural nitrogen losses to enhance the environmental sustainability under Mediterranean conditions. *Agricultural Water Management*, *230*, 105966. https://doi.org/10.1016/j.agwat.2019.105966

Maresma, Á., Ariza, M., Martínez, E., Lloveras, J., & Martínez-Casasnovas, J. (2016). Analysis of Vegetation Indices to Determine Nitrogen Application and Yield Prediction in Maize (Zea mays L.) from a Standard UAV Service. *Remote Sensing*, *8*(12), 973. https://doi.org/10.3390/rs8120973

Maresma, Á., Martínez-Casasnovas, J. A., Santiveri, F., & Lloveras, J. (2019). Nitrogen management in double-annual cropping system (barley-maize) under irrigated Mediterranean environments. *European Journal of Agronomy*, *103*, 98–107. https://doi.org/10.1016/j.eja.2018.12.002

Martínez, E., Domingo, F., Roselló, A., Serra, J., Boixadera, J., & Lloveras, J. (2017). The effects of dairy cattle manure and mineral N fertilizer on irrigated maize and soil N and organic C. *European Journal of Agronomy*, *83*, 78–85. https://doi.org/10.1016/j.eja.2016.10.002

OJ (2019). Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003. http://data.europa.eu/eli/reg/2019/1009/oj Accés 02/10/2022

Peyraud, J.L., & MacLeod, M. (2020). Study on Future of EU livestock: how to contribute to a sustainable agricultural sector? Final report. Publications Office of the European Union. ISBN: 978-92-76-20624-8

Quemada, M., & Gabriel, J. L. (2016). Approaches for increasing nitrogen and water use efficiency simultaneously. *Global Food Security*, *9*, 29–35. https://doi.org/10.1016/j.gfs.2016.05.004

Römkens, P.F.A.M., Rietra, R.P.J.J., Kros, J., Voogd, J.C., & de Vries, W., (2018). *Impact of cadmium levels in fertilisers on cadmium accumulation in soil and uptake by food crops*. 115p. Wageningen, the Netherlands: Wageningen Environmental Research. https://edepot.wur.nl/451353

Ryan, J., Monem, M. A., & Amri, A. (2009). Nitrogen fertilizer response of some barley varieties in semi-arid conditions in Morocco. *Undefined*

Sadras, V.O., & McDonald, G. (2011). Water use efficiency of grain crops in Australia: principles, benchmarks and management. Grains Research and Development Corporation, South Australian Research and Development Institute and University of Adelaide. https://grdc.com.au/__data/assets/pdf_file/0030/159186/grdcpublicationwateruseefficiencyofgraincropsinaustraliapdf.pdf.pdf ISBN: 978-1-921779-40-4

Sisquella, M., Lloveras, J., Álvaro, J., Santiveri, P., & Cantero, C. (2004). Técnicas de Cultivo para la Producción de Maíz, Trigo y Alfalfa en Regadíos del Valle del Ebro. Fundació Catalana de Cooperació: Barcelona, Spain. ISBN 846887860X

Telkar, S.G., Solanki, S.P.S, Chouhan, S., Kumar, R. & Nikas, S.B. (2012). Crop Lodging on Cereals: Causes, Effect and Control. Biomolecule Reports. ISSN:2456-8759

Webb, J., Sorensen, P., Velthof, G. L., Amon, B., Pinto, M., Rodhe, L., Salomon, E., Hutchings, N., Burczyk, J., & Reid, J. E. (2011). Study on variation of manure N efficiency throughout Europe. (Final report). AEA Technology plc. http://ec.europa.eu/environment/water/water-nitrates/pdf/Man_N_Eff_Final%20Report.pdf Accessed 21/01/2015

Xiao, G., Zhang, Q., Wang, R., Yao, Y., Zhao, H., Bai, H., & Xiong, Y. (2009). Effects of Temperature Increase on Pea Production in a Semiarid Region of China. *Https://Doi.Org/10.4137/ASWR.S2488*, *2*, 31–39. https://doi.org/10.4137/ASWR.S2488

Yagüe, M. R., & Quílez, D. (2010). Direct and residual response of wheat to swine slurry application method. *Nutrient Cycling in Agroecosystems*, *86*(1), 161–174. https://doi.org/10.1007/s10705-009-9280-9

Yagüe, M. R., & Quílez, D. (2013). Residual Effects of Fertilization with Pig Slurry: Double Cropping and Soil. *Agronomy Journal*, *105*(1), 70–78. https://doi.org/10.2134/agronj2012.0191