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REVIEW

REINTEGRATION OF CROP-LIVESTOCK SYSTEMS IN EUROPE: AN OVERVIEW

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SUPPLEMENTARY MATERIALS

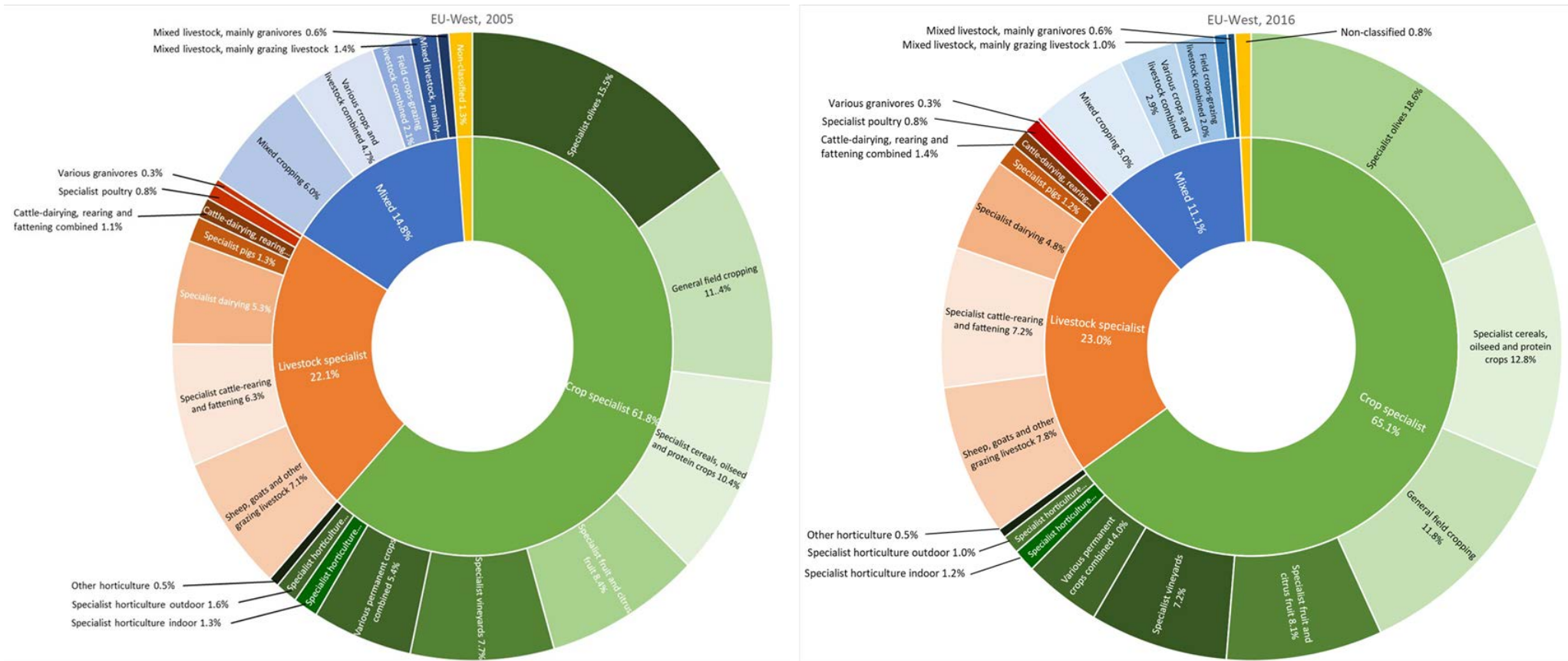


Fig. S1 The percentages of farms with a mixed or specialised farm type differentiated into crop and livestock specialists for 2005 and 2016 in western Europe (EU-West), including Belgium, Denmark, France, Greece, Germany, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, and the United Kingdom. Source from Eurostat^[1]. Database: ef_m_farmleg.

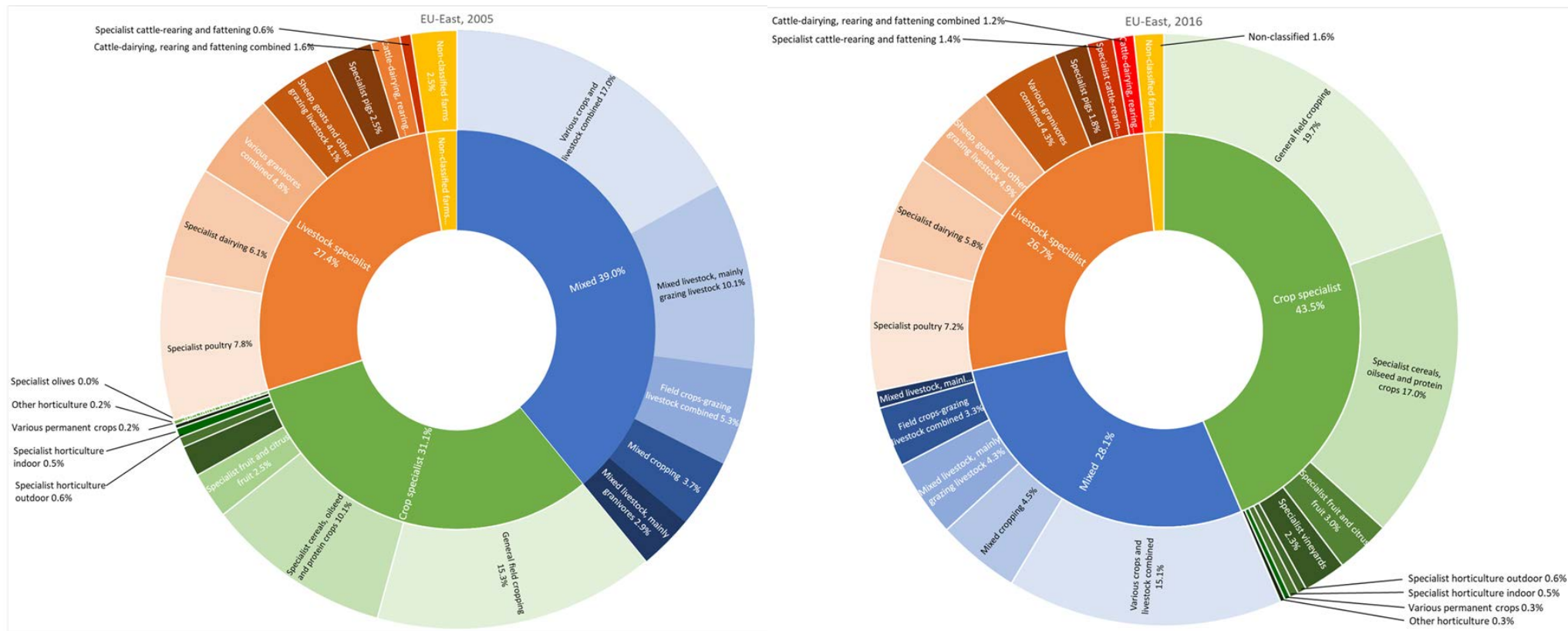


Fig. S2 The percentages of farms with a mixed or specialised farm type differentiated into crop and livestock specialists for 2005 and 2016 in eastern Europe (EU-East), including Austria, Bulgaria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia and Slovenia. Source from Eurostat^[1]. Database: ef_m_farmleg.

Table S1 Effects of livestock on soil structure, C and N contents and yield in cropping systems within EU and non-EU countries

Livestock in arable-ley rotations							
Indicator	Country	Ley composition	Livestock	Stocking rate	Soil depth (cm)	Comments	References
Soil N	Belgium	Grass-clover	Cattle	Stocked to maintain 7 cm sward height	0–30	Residual soil N at the end of the growing season was higher in the grazed ley (63–66 kg·ha ⁻¹ N) than the cut ley (33–55 kg·ha ⁻¹ N)	[2]
	Denmark	Grass-clover	Cattle	1237 grazing days ha ⁻¹	0–100*	Cattle grazing grass-clover ley with no additional slurry applications did not significantly increase N leaching compared to the ungrazed control	[3]
	The Netherlands	Grass-clover**	Sheep and cattle	128 cattle LU, 14 sheep LU	0–30	Dairy cattle excreta to pasture provided 150 kg·ha ⁻¹ ·yr ⁻¹ N	[4]
	Finland	Grass and Grass-clover***	Cattle	Variable	0–180*	17 and 9 kg·ha ⁻¹ N was leached during the ley period for the fertilised grass and unfertilised grass-clover leys respectively	[5]
	Denmark	Grass-clover	Cattle	1.1 and 1.4 LU·ha ⁻¹	0–100*	Manure inputs from cattle grazing provided 141 kg·ha ⁻¹ N at both experimental sites. 9–64 kg·ha ⁻¹ ·yr ⁻¹ N was leached during the ley period	[6]
	Denmark	Grass-clover	Cattle	0.9 and 1.4 LU·ha ⁻¹	0–200*	Increasing livestock grazing density to 1.4 LU·ha ⁻¹ increased N input by 40 kg·ha ⁻¹ ·yr ⁻¹ N and N leaching by 6 kg·ha ⁻¹ NO ₃ -N.	[7]
Soil C	England	Grass-clover	Sheep	n.d.	0–40	SOC increased by 0.33 t·ha ⁻¹ ·yr ⁻¹ in the first 28 years of the arable-ley rotation when grazed, equivalent to an annual SOC increase of 0.6%	[8]
	Australia	Grass-legume	Sheep	Variable	0–30	Grazed leys increased SOC by 0.5–0.7 t·ha ⁻¹ ·yr ⁻¹ C, however, this is quickly depleted by tillage and crop residue management	[9]
	Belgium	Grass-clover	Cattle	n.d.	0–10	SOC increased by 7.5 g·kg ⁻¹ dry soil in grazed leys compared to cut only leys	[10]
	Denmark	Grass-clover	Cattle	1.1 and 1.4 LU·d ⁻¹ ·ha ⁻¹	0–100*	Cattle grazing excretal returns were estimated to provide 1.6–2.6 t·ha ⁻¹ ·yr ⁻¹ C	[6]
	England	Grass-clover	Sheep	n.d.	0–15	SOC increased by 0.23% for grazed ley compared to 0.17% for a cut-only ley. SOC increases were limited to 2–3 cm of topsoil	[11]
Soil structure	Belgium	Grass-clover	Cattle	n.d.	5–10	Soil bulk density under grass-clover ley (1.41 g·cm ⁻³) was similar to permanent arable (1.40 g·cm ⁻³) and significantly higher than permanent grassland (1.14 g·cm ⁻³) and temporary arable (1.29 g·cm ⁻³)	[10]
	Scotland	Grass-clover	Sheep	2.5 sheep LU·d ⁻¹ ·ha ⁻¹	0–35	Grazing had little effect on soil structure	[12]
Yield	Belgium	Grass-clover	Cattle	Stocked to maintain 7 cm sward height	0–30	No difference in yield observed in maize crops following grazed or cut leys	[2]
	Scotland	Grass-clover	Sheep	n.d.	0–15	Crop yield was maintained with N ₂ fixing crops, grazing livestock, and manure applications	[13]
	Belgium	Grass-clover	Cattle	n.d.	0–90	Maize yield was 85%, 21% and 2% greater in grazed arable-ley rotations than in continuous arable system when 0, 75 and 180 kg·ha ⁻¹ N mineral fertiliser was used	[14]
Livestock in Forage Cropping Systems							
Indicator	Country	Grazed forage	Livestock	Stocking rate	Soil depth (cm)	Comments	Authors
Soil N	New Zealand	Turnip	Cattle	Stocked at 4 kg turnip DM cow ⁻¹ ·d ⁻¹	0–45****	In comparison to permanent pasture, summer cattle forage grazing and autumn re-grassing increased N leaching in drainage water by 84% to 21 kg·ha ⁻¹ N between trial commencement in 2006 and end of drainage season in 2008	[15]
	Canada	Hairy vetch, pea/oat mix, Lentil, Soybean, Sweet clover, mixture (see paper)	Sheep	1111-1667 sheep days ha ⁻¹	0–30	Higher proportions of N ₂ fixing crops in grazed pasture increased N uptake in following arable crops. Wheat N uptake from grazed and ungrazed plots was 107 and 98 kg·ha ⁻¹ N, respectively	[16]
	England	Turnip	Sheep	n.d.	0–60*	155 and 193 kg·ha ⁻¹ N was leached from two sites on the experimental farm under autumn sheep grazing stubble turnips	[17]
Soil C	USA	Spring pea	Sheep	100-150 ewes d ⁻¹ ·ha ⁻¹	0–150	Annual sheep grazing of forage crops had no effect on total soil profile (0–150) SOC stocks	[18]
	Germany	Winter wheat	Cattle	0.7 LU·ha ⁻¹	0–90	SOC increased by 0.23 t·ha ⁻¹ ·yr ⁻¹ in the mixed farming system, utilising leys and winter wheat stubble grazing, but was not significantly greater than the stockless ley system or stockless cash crop system due to annual variation. SOC was significantly higher for 0–30 cm for mixed farming (5.4 t·ha ⁻¹) compared to stockless ley farming and stockless cash crop production (5.1 t·ha ⁻¹ and 4.7 t·ha ⁻¹ , respectively). There was no significant difference in SOC for 30–90 cm between systems	[19]
	USA	Oat, rye and turnip	Cattle	n.d.	0–20	SOC was greatest under winter cover crop management (24.5 g·kg ⁻¹) than cool-season pastures (21 g·kg ⁻¹), and continuous corn (15.8 g·kg ⁻¹). This was attributed to tillage incorporating crop and cattle manure residues into the soil	[20]
Soil structure	Australia	Canola	Sheep	800 dry sheep equivalents d ⁻¹ ·ha ⁻¹	0–10	Winter grazing significantly increased surface (0–5 cm) bulk density pre-sowing (1.33, 1.49, 1.45 g·cm ⁻³ ungrazed, dry grazed and wet grazed respectively) but did not significantly increase post-sowing (1.28, 1.30, 1.29 g·cm ⁻³ ungrazed, dry grazed and wet grazed, respectively) compared to the ungrazed control	[21]
	USA	Oat, rye and turnip	Cattle	n.d.	0–20	No effect of cattle grazing in the winter cover crop treatment on soil bulk density and compaction throughout the trial due to annual conventional tillage. Soil penetration resistance was higher in the grazed winter cover crop (921 kPa) and grazed cool-season pastures (928 kPa) than continuous arable (655 kPa)	[20]
Yield	USA	Spring pea	Sheep	100-150 ewes d ⁻¹ ·ha ⁻¹	0–150	Winter wheat in a mixed livestock rotation received 10–50 kg·ha ⁻¹ less N but increased yield by 7.8% compared with conventionally cropped wheat	[18]

Australia	Wheat	Sheep	29 dry sheep equivalents ha ⁻¹	0–250	Sheep grazing significantly reduced grain yield (7.9 t·ha ⁻¹ grazed only and 6.9 t·ha ⁻¹ grazed and mown) compared to ungrazed control (12.1 t·ha ⁻¹)	[22]
Canada	Hairy vetch, pea/oat mix, Lentil, Soybean, Sweet clover, mixture (see paper)	Sheep	1111-1667 sheep days ha ⁻¹	0–30	For the green manure grazing experiment in 2011, sheep grazing increased grain N content (141 and 131 g·kg ⁻¹ N grazed and ungrazed respectively), N uptake (73 and 60 kg·ha ⁻¹ N grazed and ungrazed, respectively), and wheat DM production (8.27 and 7.72 t·ha ⁻¹ grazed and ungrazed, respectively) but did not significantly increase yield	[16]
USA	Crimson clover – rye (low N input), ryegrass – rye (high N input)	Cattle	Stocked to consume 90% of forage	n.d.	Cattle grazing increased corn grain yield under no-tillage management (2.63 and 2.40 t·ha ⁻¹ grazed and ungrazed, respectively) but did not increase under conventional tillage (0.56 and 1.34 t·ha ⁻¹ grazed and ungrazed, respectively). Soybean yield was negatively affected by cattle grazing under no-tillage management (1.97 and 2.41 t·ha ⁻¹ grazed and ungrazed, respectively) and conventional tillage (1.40 and 1.53 t·ha ⁻¹ grazed and ungrazed, respectively)	[23]
Australia	Wheat	Sheep	High-short (HS) 67 sheep ha ⁻¹ 31 days, low-long (LL) 33 sheep ha ⁻¹ for 62 days, low-short (LS) 33 sheep ha ⁻¹ for 31 days.	0–180	No significant effect of grazing on average grain yield (3.97 t·ha ⁻¹ HS, 3.65 t·ha ⁻¹ LL, and 4.07 t·ha ⁻¹ LS) compared to ungrazed control (3.61 t·ha ⁻¹)	[24]

Livestock in Crop Stubble Grazing Systems

Indicator	Country	Grazed crop	Livestock	Stocking rate	Soil depth (cm)	Comments	Authors
Soil N	Australia	Canola, wheat	Sheep	Variable.	0–185	Stubble grazing increased soil mineral N at the end of the growing season compared to control (no grazing) for canola in 2010 (178 and 205 kg·ha ⁻¹ N), wheat in 2011 (93 and 126 kg·ha ⁻¹ N), and wheat in 2012 (99 and 144 kg·ha ⁻¹ N), respectively	[25]
	USA	Wheat	Sheep	816 sheep days ha ⁻¹	0–60	Surface soil NO ₃ -N (0–15 cm) was lower in sheep grazed fallow (27 mg·kg ⁻¹ N) than tilled (35 mg·kg ⁻¹ N) or chemically controlled fallow (36 mg·kg ⁻¹ N) due to residue removal	[26]
Soil C	Israel	Wheat	Sheep and goats	n.d.	0–10	SOC pool was 16% greater under stubble grazing than no stubble grazing due to manure derived OM	[27]
	Syria	Durum wheat, lentil, chickpea, pasture Vetch, pasture medic, watermelon	Sheep	Variable.	0–20	Crop stubble grazing had a significant effect on SOM, reducing SOM from 264 t·ha ⁻¹ SOM (ungrazed) to 251 t·ha ⁻¹ SOM (high intensity grazing) and 253 t·ha ⁻¹ SOM (medium intensity grazing)	[28]
	Argentina	Maize, sunflower	Cattle	n.d.	0–5	SOC declined under cattle grazing of maize and sunflower stubble compared to ungrazed plots (8.83 g·kg ⁻¹ C and 10.06 g·kg ⁻¹ C, respectively)	[29]
Soil structure	Australia	Canola, wheat	Sheep	Variable	0–185	Sheep grazing significantly increased soil strength and bulk density. Winter wheat grazing in 2012 increased surface (0–5 cm) bulk density (1.28 and 1.27 g·cm ⁻³ for stubble grazed and winter and stubble grazed respectively) compared to the ungrazed control (1.18 g·cm ⁻³). Soil strength also significantly increased from 150 kPa ungrazed to 360 and 524 kPa under stubble grazing and winter wheat and stubble grazing respectively. Sheep grazing canola crop in 2011 also significantly increased soil strength from 308 kPa ungrazed to 494 and 563 kPa under stubble grazing and winter canola and stubble grazing, respectively	[25]
	Israel	Wheat	Sheep and goats	n.d.	0–10	Soils under crop stubble grazing had 15% greater aggregate stability than no grazing	[27]
	USA	Wheat	Sheep	816 sheep days ha ⁻¹	0–60	Surface soil bulk density (0–15 cm) was higher in sheep grazed fallow (1.28 g·cm ⁻³) than tilled (1.18 g·cm ⁻³) or chemically controlled fallow (1.21 g·cm ⁻³)	[26]
	Argentina	Wheat	Cattle	4 LU·ha ⁻¹ (standard stocking rate) or 12 LU·ha ⁻¹ (high stocking rate)	0–15	Prior to maize crop establishment, topsoil (0–5 cm) bulk density was lower under high intensity grazing (1.26 g·cm ⁻³) than ungrazed control (1.31 g·cm ⁻³) and standard stocking rate grazing (1.31 g·cm ⁻³). There was no significant effect of grazing on subsoil (5–15 cm) bulk density (1.17 g·cm ⁻³ ungrazed control and 1.17 g·cm ⁻³ high intensity)	[30]
	Australia	Wheat	Sheep	358 dry sheep equivalents d ⁻¹ ·ha ⁻¹	0–10	Summer grazing increased topsoil bulk density (0–5 cm) (1.25 and 1.18 g·cm ⁻³ grazed and ungrazed, respectively at Greenethorpe, and 1.32 and 1.27 g·cm ⁻³ grazed and ungrazed, respectively at Tootool). Topsoil soil strength at field capacity also increased (0–10 cm) (673 and 504 kPa grazed and ungrazed respectively at Greenethorpe, and 337 and 273 kPa grazed and ungrazed respectively at Tootool). No significant effects were observed for infiltration rate	[21]
Yield	Australia	Canola, Wheat	Sheep	Variable	0–185	Negative yield responses to crop stubble grazing were only observed when stubble cover was <70% (or 2 t·ha ⁻¹). Winter wheat grazing increased yield by 0.6 t·ha ⁻¹ (6.9 and 7.5 t·ha ⁻¹ ungrazed and winter and stubble grazed). No significant effects of grazing on canola were observed (3.4 t·ha ⁻¹ ungrazed, 3.3 t·ha ⁻¹ stubble grazed, and 3.1 t·ha ⁻¹ winter and stubble grazed)	[25]
	Brazil	Wheat	Cattle	Stocked to maintain 25 cm canopy height	0–20	Cattle grazing reduced subsequent wheat yield by 8.8 kg·ha ⁻¹ ·d ⁻¹ of grazing	[31]
	USA	Wheat	Sheep	816 sheep days ha ⁻¹	0–60	Sheep grazing crop stubble had no significant effect on grain yield (3.5 t·ha ⁻¹) compared to chemically controlled fallow (3.4 t·ha ⁻¹) and tillage-controlled fallow (3.6 t·ha ⁻¹)	[26]
	Argentina	Wheat	Cattle	4 LU·ha ⁻¹ (standard stocking rate) or 12 LU·ha ⁻¹ (high stocking rate)	0–15	Maize grain yield was higher under high intensity grazing (8.5 kg·ha ⁻¹) than the ungrazed control (6.5 kg·ha ⁻¹) and standard intensity grazing (7.6 kg·ha ⁻¹)	[30]
	Australia	Wheat	Sheep	358 dry sheep equivalents d ⁻¹ ·ha ⁻¹	0–10	No significant effects of stubble grazing on crop yield (2.1 t·ha ⁻¹ and 2.0 t·ha ⁻¹ grazed and ungrazed, respectively at Greenethorpe, and 1.3 t·ha ⁻¹ grazed and ungrazed at Tootool)	[21]

Note: n.d. indicates not determined. 1LU = 500 kg liveweight. SOC = soil organic carbon. SOM = soil organic matter. * = suction cups were used for N leaching measurements. ** indicates grass-clover indicates *Lolium perenne* L. – *Trifolium repens* L. *** grass-clover composition of Saarijärvi et al.^[5] includes white clover (*Trifolium repens* L.), alsike clover (*Trifolium hybridum* L.), timothy (*Phleum pratense*), meadow fescue (*Festuca pratensis*), and smooth meadow grass (*Poa pratensis*). **** an isolated mole and pipe drain system was used for N leaching measurements.

Scientific names of plant species

Hairy vetch (*Vicia villosa*), pea/oat mix (*Pisum sativum* – *Avena sativa*), Lentil (*Lens culinaris*), Soybean (*Glycine max*), Sweet clover (*Melilotus officinalis*), mixture (see paper). Canola (*Brassica napus*). Wheat (*Triticum aestivum* (EU countries) or *Triticum vulgare* (Brazil)). Spring pea (*Lathyrus vernus*). Turnip (*Brassica rapa subsp. Rapa*). Maize (*Zea mays*). Rye (*Secale cereal* L.). Crimson clover (*Trifolium incarnatum* L.). Ryegrass (*Lolium multiflorum* Lam). Sunflower (*Helianthus annuus* L.). Chickpea (*Cicer arietinum*). Pasture vetch (*Vicia sativa*). Pasture medic (*Medicago* spp). Watermelon (*Citrullus vulgaris*).

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