

A whole-systems approach for assessing measures to improve arable ecosystem sustainability

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Abstract. There is increasing pressure on the agricultural industry to maintain or increase production of high-quality food while maintaining long-term environmental sustainability. UK and EU policies and practices have been developed and implemented in an attempt to improve the sustainability and efficiency of arable farming and satisfy these potentially conflicting requirements. However, to the authors' knowledge, there has been no attempt to quantify whether new interventions have the desired effect on improving sustainability at a whole-systems level. Most studies focus on one, or a few, elements of a specific system and therefore fail to account for trade-offs and conflicts between the many different interacting components. Here, we propose a whole-systems approach based on a suite of indicators for a complete and holistic assessment of the efficacy of policies to improve economic, environmental, and ecological sustainability.

Key words: *arable food webs; crop yield; financial margins; invertebrates; soil; sustainability; weeds.*

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Background

The intensification of agricultural production in Europe since the 1950s has resulted in increases in yield, but at heavy environmental cost. Agricultural land in the European Union now covers almost half of the total land area—over 100 million hectares (ha) under arable cultivation, 65 million ha permanent grassland, and 12 million ha perennial crops (Henle et al. 2008). The negative impact of intensification over such a large area has raised serious concerns about loss of biodiversity, ecosystem services, and the sustainability of agricultural systems. This is of particular concern because the need to increase food production to meet the demands of rising human population (Defra 2011) is in conflict with the need to conserve biodiversity and ensure long-term sustainability.

In an effort to achieve a balance between these potentially conflicting goals, many practices have been developed that aim to improve the agricultural environment. These are implemented primarily through policy such as agri-environment schemes (AESs) which were developed following the Common Agriculture Policy reform in the late 1980s and early 1990s (Carey et al. 2003). Such measures are designed to protect and enhance the farmland habitat by providing farmers with subsidies to adopt environmentally friendly farming techniques. The overall objectives are to counteract the negative effects

of modern agriculture by reducing pollution from loss of soil, nutrients, and pesticides; protecting biodiversity; restoring landscapes; and preventing rural depopulation (Kleijn and Sutherland 2003).

Although policy incentives are frequently used to help reduce the environmental impact of intensive farming systems, systematic evaluations of such schemes are relatively rare in the peer-reviewed literature and most impact assessments have focused on biodiversity without reference to wider system components (e.g., pollution, yield losses, soil degradation). The results of these biodiversity studies are frequently inconsistent, and the direction of effect depends largely on the specific options that were selected for study, the target habitat, and the landscape context (Bengtsson et al. 2005). For example, agroecological practices in general can have a positive effect on numbers of birds (Vickery et al. 2002), mammals (Tattersall et al. 2002), arthropods (Attwood et al. 2008) including pollinators (Pywell et al. 2006) and natural enemies (Jeanneret et al. 2016) and plant species diversity (Taylor and Morecroft 2009). However, positive effects were only detected for half of the species groups that were assessed (Kleijn et al. 2006) and many examples of environmental management options can be found that have no effect on a specific target group (Marshall et al. 2006, Carvell et al. 2007, Fuentes-Montemayor et al. 2011).

One “recipe” cannot therefore benefit all taxa, and it is evident from these mixed results that what is optimal for one purpose may be suboptimal or even counter-productive for another (Carey et al. 2003). This

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highlights the potential for conflicting goals in farmland management where the requirements necessary for the conservation of different components of farmland biodiversity are at odds with each other and may be very different from management recommendations designed to protect environmental health or enhance food security (Henle et al. 2008).

Research on food security has concentrated on trends in yields from intensely managed crops. Analysis indicates a leveling in yield in recent decades or even a decline, despite continued availability of inputs. Remedies have been sought largely through increasing the physiological performance of crops and the fine-scale management of resources such as nutrients (Lobell et al. 2009). While some authors recognize the contributions of factors such as soil condition (Cassman 1999), a whole-systems appraisal that takes account of the biological interactions between crop plants, soil, pests, and food webs is rarely attempted and changes in management to improve crop performance are rarely assessed in terms of impact on other components of the arable system including biodiversity and environmental impact.

Similarly, the emphasis in studies of wider environmental impact, for example on agrochemical pollution, has been to quantify inputs, uptake, offtake, and losses and the corresponding use-efficiencies (Liu et al. 2010, MacDonald et al. 2011). The role of local process and

biological interaction is acknowledged, yet ultimately solutions rely on change in management at the scale of the field or farming system. The influence of fine-scale interactions between plants—not only crops but also in-field weeds, field margins, and surrounding vegetation—and the associations between plants, soil microorganisms, and invertebrates is rarely accounted for.

There is therefore an urgent need to design evaluation studies for the introduction of any new agricultural policy, practice, or management strategy to provide an assessment of the impact on the whole system, rather than just targeting specific elements in isolation (European Food Safety Authority, EFSA 2010). Comprehensive environmental risk assessment and monitoring can provide a feedback mechanism for iterative improvement of the outcome of future policies for environmental and conservation benefit (Fig. 1).

Indicators for monitoring impact should therefore be selected that represent all key components of agricultural systems. Here, we present a systems approach for monitoring impact that takes account of ecosystem functions and the trade-offs between them. This whole-systems approach not only deals with biodiversity-related indicators that have historically been the focus for AESs and agroecological practices in general, but also takes into account the wider impacts of a change in management or intervention on all components of

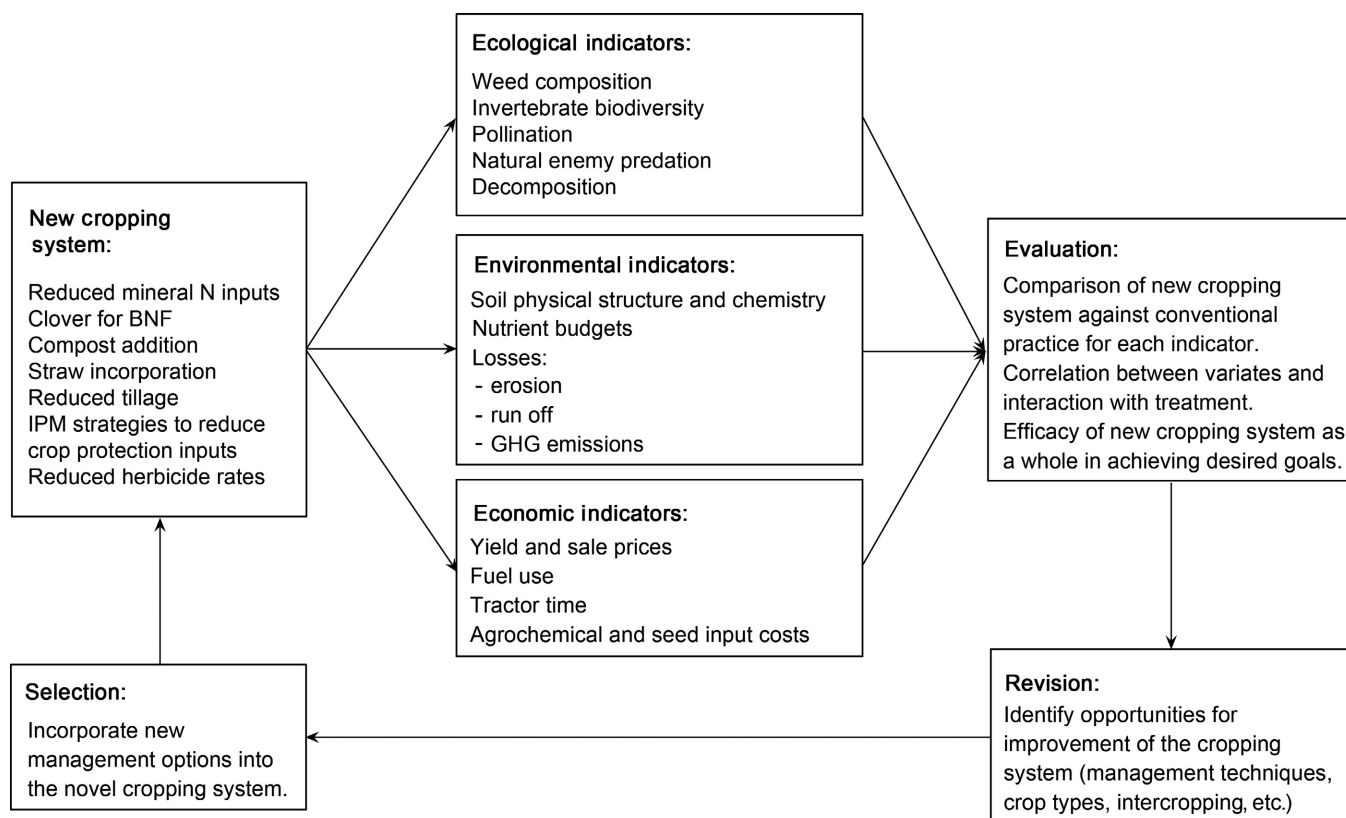


Fig. 1. A whole-system, iterative approach to assessing and reviewing the impact of a new cropping system on the arable ecosystem using a suite of indicators.

the system that relate to sustainability, including economic and environmental functions as well as ecological processes.

Defining the System

Arable ecosystems can be defined in terms of three elements (Table 1). First (Table 1, Column 1) are the required outputs: (A) farmland biodiversity to provide ecosystem services through ecological interactions between organisms; (B) the protection of soil, air, and water quality for environmental health to maintain yields over long periods without requiring increased rates of agrochemical inputs; and (C) products (e.g., food, fuel, and fiber) necessary for economic viability of the farming community. Second (Table 1, Column 2) are the management interventions necessary to achieve these outputs, particularly the crop types, varieties and crop rotation, cultivation techniques, agrochemical inputs, and conservation or environmental protection strategies. Third (Table 1, Column 3) are the system

components and processes (plants, animals, and microorganisms and their interactions) which provide the mechanism by which management interventions result in the desired outcomes.

System Indicators

For an accurate assessment of the impact of a new policy or management practice on the whole system, a suite of indicators must be selected that together represent all key components of the system in question. Here, we propose an indicator set appropriate for holistic assessment of arable ecosystems (Table 2), grouped according to the type of system process they represent (three categories A to C from Table 1).

Category A is ecological indicators including representatives of primary producers (weed seed bank, emerged weeds, and semi-natural vegetation) that support arable food webs including natural enemies, pollinators, and decomposers. The arable weed seed bank provides the basis for within-field weed diversity and confers a degree

Table 1. Summary of desired outputs from arable ecosystems, the management interventions designed to achieve these goals, and the system components and processes that provide the mechanism by which management results in output.

1. Required output	2. Management intervention	3. System component
A. Enhancing biodiversity for provision of ecosystem services (nutrient cycling, pollination, pest control): <i>Ecological indicators</i>	Reduced herbicide and specific targeting of competitive weeds to achieve a 5–10% cover of beneficial broadleaved weeds in-field Reduced/threshold pesticide application to minimize non-target effects Conservation headlands with no fertilizer or herbicide application Multifunctional sown margins for increasing resource availability for natural enemies and pollinators	1. Weeds supporting arable food webs 2. Regulation of pest and disease populations 3. Pollination 4. Decomposition and nutrient cycling
B. Minimizing losses through erosion, runoff, leaching, and GHG emissions: <i>Environmental indicators</i>	Non-inversion tillage to improve soil physical structure Stubble and organic matter incorporation Controlled traffic to reduce compaction Cover cropping to retain nutrients overwinter for subsequent crop Variable rate agrochemical inputs tailored to soil nutrient supply and disease incidence Engineered riparian buffers and multifunctional margins to reduce losses from field	5. Erosion control 6. Enhancing soil water quality and reducing losses 7. Air pollution mitigation
C. Maintaining or improving farmed product (yield), food security, financial security, and human health: <i>Economic indicators</i>	Alternative sources of nutrients to compensate for reduced mineral fertilizer Enhancing uptake of existing plant nutrients through improved soil structure Reducing loss of available nutrients through improved soil structure Selection of crop varieties to maximize nutrient use efficiency and crop–weed competition under reduced inputs Integrated Pest and Management strategies to compensate for reduced crop protection chemical applications	8. Primary productivity and production efficiency 9. Gross profit margin, estimated as revenue offset against input costs, fuel use, and tractor time

Note: This framework was developed for the impact assessment of an Integrated Management System at the James Hutton Institute's Centre for Sustainable Cropping, Dundee, UK (Hawes 2016).

Table 2. A suite of 12 indicators, selected to represent each of the system components described in Table 1.

System component (Column 3, Table 1)	Indicator set	CSC case study example	Method
A1. Plants supporting arable food webs	A. Arable weed seed bank	The primary source of biological diversity within cropped fields, crucial to the functioning of arable systems. Confers a high degree of resilience to change in management	Ex situ germination of weed seeds from soil samples following the emergence technique in Hawes et al. (2003)
	B. Emerged weed flora	In-field weeds cause yield loss at high densities, but are also an essential resource for arable food webs. Over winter, weeds can stabilize soil and reduce leaching by taking up excess fertilizer or nutrients released by decaying crop matter	Quadrat counts of emerged weeds and percent cover assessments in relation to crop cover
	C. Landscape composition	Semi-natural landscape features and habitats provide essential or complimentary resources to all taxa including natural enemies and pollinators	GIS assessment of habitat maps
A2. Regulation of pest and disease populations	C. Predation and parasitism rates	Functional groups of invertebrates are essential for maintaining ecosystem services, particularly natural enemies that can help control crop pests. Their abundance is assessed as part of the monitoring program for arable food webs and, together with measure of predation rates on bait plants/cards, can be related to prey density and abundance of potential competitors with which they interact	Pitfall trapping in spring and monthly vortis suction sampling. Samples collected from within the cropped area and in field margins
	D. Crop pathogens—disease incidence and spread	Integrated Pest and Management (IPM) strategies are used to enhance disease control without the need for increased use of crop protection chemicals. Effective deployment of IPM strategies requires close monitoring of pathogen populations	Disease scoring is carried out throughout the cropping season, and soil is sampled for soil-borne pathogens at the beginning and end of season
A3. Pollination	E. Pollination activity	Declining insect pollinator numbers have the potential to affect the productivity of insect-pollinated crops. However, there are little quantitative data to inform policy and advise land owners on the impact of management strategies for improving insect pollinator abundance	Pollinators are monitored using transect walks along field margins and into flowering crops. Bagged plants are used to measure to pollination rates
A4. Decomposition and nutrient cycling	F. Litter decomposition rate in relation to microbial diversity and detritivore abundance	The diversity and abundance of decomposers in arable soil have an impact on a range of system functions, particularly carbon turnover and nitrogen dynamics, and are therefore important in low input systems where a sustainable nutrient supply is essential for maintaining yields	Litter decomposition rate is measured as loss in mass of dried barley straw over a single growing season using standard litter bags with 2-mm mesh size
B5. Erosion control and nutrient retention	G. Soil physical structure and carbon content	The average rate of soil loss by erosion on arable land across Europe is estimated between 3 and 40 t·ha ⁻¹ ·yr ⁻¹ (Verheijen et al. 2009), and losses of nitrogen through soil erosion are estimated at 60 kg N·ha ⁻¹ ·yr ⁻¹ (from Pimentel et al. 1995). This raises concerns about nutrient depletion, decreased soil aggregation, loss of productivity, and off-site impacts through sedimentation and eutrophication of downstream water bodies	Soil biophysical characteristics are measured using the in situ shear vane test together with measures of bulk density and carbon content
B6. Enhancing soil water quality	H. Soil water quality	Average nitrogen losses through leaching from arable land across Europe are estimated to be around 36 kg N·ha ⁻¹ ·yr ⁻¹ (Ngetich et al. 2014) resulting in a decrease in crop production efficiency and increases in water pollution	Soil water quality is measured using ceramic cup lysimeters to collect soil water to depths of 10, 30, and 50 cm

Table 2. Continued.

System component (Column 3, Table 1)	Indicator set	CSC case study example	Method
B7. Air pollution mitigation	I. Carbon footprint	The latest UK Greenhouse Gas Inventory estimates the proportion of the nation's overall carbon footprint due to agriculture to be around 8%, 75% of which is directly related to fertilizer use from production, application, and direct nitrous oxide emissions (Choudrie et al. 2008)	There are a number of online tools for calculating carbon footprint. Here, we use The Cool Farm Tool (coolfarmtool.org) which calculates the carbon footprint in terms of kg CO ₂ equivalents
	J. Direct measures of GHG emissions	Losses of N through gaseous emissions can amount to 52.5 kg N·ha ⁻¹ ·yr ⁻¹ on average across European arable crops (Leip et al. 2008). Emissions vary with crop, tillage practice, and inputs, but combinations designed to minimize emissions are rarely reported	Gas samples of methane (CH ₄), carbon dioxide (CO ₂), and nitrous oxide (N ₂ O) from field soil and crop plants are collected using gas exchange boxes
C8. Primary productivity and production efficiency	K. Nutrient availability, plant biomass production, yield, and product quality	Nutrient availability correlates with plant biomass production and ultimately crop yield. However, nutrient inputs (particularly nitrogen) can be environmentally damaging. Sustainable management must therefore minimize inputs while maintaining yield. This may be achieved through use of biological nitrogen fixation (can provide >50 kg·ha ⁻¹ ·yr ⁻¹), precision agriculture, and use of renewable sources of nutrients	Soil nutrient availability is assessed annually using chemical analyses of soil samples collected in spring. Plant biomass and tissue N content are measured in the month before harvest as %C, %N, and dry mass of monocot and dicot weeds, crop stems, and grain
	L. Production efficiency and gross financial margins	Management for environmental protection may be at odds with management for profit. However, if an economic cost is incurred in the short term, there may be benefits to longer term yield stability and system health that are difficult to translate into financial terms. Economic assessments of natural capital may be estimated as financial loss in the absence of different components of natural systems (e.g., Costanza et al. 1997)	The economic impact of a new management system or intervention can be assessed through a basic comparison of input costs, fuel use, tractor time, and product sale price, taking into account differences in quality of the harvested product, for example, through calculations based on marketable yield

Note: For each indicator set, an example is given from the James Hutton Institute's Centre for Sustainable Cropping long-term platform, along with a brief description of the method used for monitoring.

of resilience in the emerged weed community to change in management (Hawes et al. 2005). Functional diversity and composition of the emerged flora are necessary to support a wide range of invertebrate trophic and functional groups (Hawes et al. 2003, 2009, 2010, Karley et al. 2008, Squire et al. 2009, Storkey et al. 2013) that provide essential ecosystem services such as pollination, natural enemy predation of crop pests, and decomposition of dead organic matter in the soil (Dungait et al. 2013, Shackelford et al. 2014, Hawes 2016, Jeanneret et al. 2016).

Category B covers the environmental indicators, focusing on soil, water, and air quality. These include soil water quality, leaching and runoff, soil carbon and physical structure which is negatively affected by intensification (Squire et al. 2015) and influences biological resilience (Griffiths et al. 2015), risk of erosion (Lewis et al. 2013), and resistance to root penetration (Valentine et al. 2012). Greenhouse gas emissions and carbon footprint calculations also provide an estimate of environmental impact, based on agrochemical inputs, fuel use, and cultivation practices and have been shown to be heavily influenced by intensity of mineral nitrogen fertilizer use (Hillier et al. 2009).

Category C is economic indicators including the key variables that affect financial margins, particularly yield, quality and product sale prices, input costs, fuel use and tractor time, or man power. These input variables can be used to calculate gross profit margin as: [revenue] – [cost of production]/[revenue]. More sustainable management practices can reduce environmental impact (Wood et al. 2006) and biodiversity loss (Bengtsson et al. 2005) but often have a negative impact on crop yield and relative profitability to the farmer (Dobbs and Smolik 1996). The ecological, environmental, and economic strands of research in agricultural systems have too often been regarded as independent. However, assessment of all three elements simultaneously will provide a better understanding of the implications of adoption of new practices on the whole system.

Whole-Systems Assessment

A key challenge in managing agroecosystems for multiple benefits is to mitigate the potential trade-offs or conflicts between different components of the system. The

most obvious example is intensive management to maximize yield which conflicts with the need to sustain long-term environmental health. Similarly, competition for space generates a trade-off between the land areas available for semi-natural habitat vs. cropped land. Within arable fields, allowing a weed understory to develop provides a benefit for arable food webs, but creates potential for competition with the crop resulting in reduced crop yield. Fewer crop protection chemical inputs can enhance invertebrate biodiversity, but reduces flexibility in the control of crop pests and disease. Increasing the soil carbon content of arable fields has a benefit in terms of erosion control and crop rooting structure, but can also enhance populations of soil-borne pathogens.

Whether or not a new management practice generates conflicts such as these, and whether they result in positive, negative, or net neutral effects in a given situation, requires a whole-systems assessment of impact. Biodiversity and environmental protection should play a major role in agroecosystem management, and the number of variables to be examined in a risk assessment should therefore be increased from the standard single-variate approach to better grasp the interactions and trade-offs between the different components. One way to broaden the scope of risk assessment and impact studies would be a more frequent use of suites of indicators to characterize the system, as proposed here. Standardized measurement of indicators over a wide range of system components would develop the field of impact and risk assessment as a multidisciplinary research discipline and would provide a more effective tool for policy. To achieve this, methods are required that allow an overall assessment of impact, taking into account the positive, negative, and neutral effects resulting from trade-offs and interactions between different elements of the system. One example of such a tool is a multiattribute decision model (MADM) hierarchical decision tree that can combine qualitative and quantitative data in a single modeling framework, and a number of software packages are available for their construction (e.g., DEXi, Bohanec et al. 2008). The whole system is divided sequentially into smaller, more quantifiable components, characterized by a set of indicators such as those described here. The indicators are organized hierarchically, and each is assigned a value on a semi-quantitative scale (e.g., 1–5) according to its relative abundance, frequency, or occurrence. The main branches of the tree, such as “economic output,” “environmental impact,” “biodiversity change,” can be weighted according to overall importance or value in a given scenario. The cumulative scores for each branch in the hierarchy can then be compared, allowing evaluation of new management practices or policies according to many potentially conflicting goals. Limits can be defined for each branch to keep the system within sustainable states. For example, a more intense form of management that would raise profit but also cause soil carbon to

decline below a critical level would be rated as inadmissible by the model and alternative management options would need to be tried to keep the model within the defined bounds. Pelzer et al. (2012) used a DEXi MADM to assess the impact of Integrated Pest Management options on arable systems, but, even here, the emphasis was primarily on crop performance rather than balancing yield against environmental and ecological impact. Further development of a more comprehensive MADM is therefore required to ensure a complete assessment across the whole ecosystem. Based on this assessment, modifications to cropping practices can then be implemented iteratively to ensure that policy decisions, when put in practice, actually achieve the goals they set out to achieve without inadvertent detriment to other components of the arable farming system.

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Literature Cited

- Attwood, S. J., M. Maron, A. P. N. House, and C. Zammit. 2008. Do arthropod assemblages display globally consistent responses to intensified agricultural land use and management? *Global Ecology and Biogeography* 17:585–599.
- Bengtsson, J., J. Ahnstrom, and A.-C. Weibull. 2005. The effects of organic agriculture on biodiversity and abundance: a meta-analysis. *Journal of Applied Ecology* 42:261–269.
- Bohanec, M., A. Messean, S. Scatasta, F. Angevin, B. Griffiths, P. H. Krogh, M. Znidarsic, and S. Dzeroski. 2008. A qualitative multi-attribute model for economic and ecological assessment of genetically modified crops. *Ecological Modelling* 215: 247–261.
- Carey, P. D., et al. 2003. The multidisciplinary evaluation of a national agri-environment scheme. *Journal of Environmental Management* 69:71–91.
- Carvell, C., W. R. Meek, R. F. Pywell, D. Goulson, and M. Nowakowski. 2007. Comparing the efficacy of agri-environment schemes to enhance bumble bee abundance and diversity on arable field margins. *Journal of Applied Ecology* 44:29–40.
- Cassman, K. G. 1999. Ecological intensification of cereal production systems: yield potential, soil quality and precision agriculture. *PNAS* 96:5952–5959.
- Choudrie, S. L., J. Jackson, J. D. Watterson, T. Murrells, N. Passant, and A. Thompson. 2008. UK Greenhouse Gas Inventory, 1990 to 2006. Annual Report for submission under the Framework Convention on Climate Change. DEFRA ISBN 0-9554823-4-2. http://www.airquality.co.uk/archive/reports/cat/07/0804161424_ukghgi-90-06_main_chapters_UNFCCC_submission_150408.pdf
- Costanza, R., R. d’Arge, R. de Groot, S. Farber, M. Grasso, and B. Hannon. 1997. The value of the world’s ecosystem services and natural capital. *Nature* 387:253–260.
- Defra. 2011. Foresight. The future of food and farming, final project report. The Government Office for Science, London, UK.
- Dobbs, T., and J. D. Smolik. 1996. Productivity and profitability of conventional and alternative farming systems: a long-term

- on-farm paired comparison. *Journal of Sustainable Agriculture* 9:63–77.
- Dungait, A. J. A., C. Ghee, J. S. Rowan, B. L. McKenzie, C. Hawes, E. R. Dixon, E. Paterson, and D. W. Hopkins. 2013. Microbial responses to the erosional redistribution of soil organic carbon in arable fields. *Soil Biology and Biochemistry* 60:195–201.
- EFSA. 2010. EFSA Panel on Genetically Modified Organisms (GMO). Guidance on the environmental risk assessment of genetically modified plants. *EFSA Journal*, 8:1–111.
- Fuentes-Montemayor, E., D. Goulson, and K. J. Park. 2011. The effectiveness of agri-environment schemes for the conservation of farmland moths: assessing the importance of a landscape-scale management approach. *Journal of Applied Ecology* 48:532–542.
- Griffiths, B. S., et al. 2015. Probing soil physical and biological resilience data from a broad sampling of arable farms in Scotland. *Soil Use and Management* 31:491–503.
- Hawes, C. 2016. Assessing the impact of management interventions in agroecological and conventional cropping systems using indicators of sustainability. Chapter 9 in A. Wezel, editor. *Agroecological practices for sustainable agriculture: principles, applications, and making the transition*. Imperial College Press, London, UK, *in press*.
- Hawes, C., G. Begg, G. R. Squire, and P. Iannetta. 2005. Individuals as the basic accounting unit in studies of ecosystem function: functional diversity in *Capsella* (shepherd's purse). *Oikos* 109:521–534.
- Hawes, C., A. J. Houghton, D. A. Bohan, and G. R. Squire. 2009. Functional approaches for assessing plant and invertebrate abundance patterns in arable systems. *Basic and Applied Ecology* 10:34–47.
- Hawes, C., G. R. Squire, P. D. Hallett, C. A. Watson, and M. Young. 2010. Arable plant communities as indicators of farming practice. *Agriculture, Ecosystems and Environment* 138:17–26.
- Hawes, C., et al. 2003. Responses of plant and invertebrate trophic groups to contrasting herbicide regimes in the Farm Scale Evaluations of genetically-modified herbicide-tolerant crops. *Philosophical Transactions of the Royal Society B: Biological Sciences* 358:1899–1913.
- Henle, K., et al. 2008. Identifying and managing the conflicts between agriculture and biodiversity conservation in Europe: a review. *Agriculture, Ecosystems and Environment* 124: 60–71.
- Hillier, J., C. Hawes, G. R. Squire, A. Hilton, S. Wale, and P. Smith. 2009. The carbon footprints of food crop production. *International Journal of Agricultural Sustainability* 7:107–118.
- Jeanneret, P., G. Begg, M. Gosme, O. Alomar, B. Reubens, J. Baudry, O. Guerin, C. Flamm, and F. Wäckers. 2016. Landscape features to improve pest control in agriculture. *Solutions* 7:48–57.
- Karley, A. J., C. Hawes, P. P. M. Iannetta, and G. R. Squire. 2008. Intraspecific variation in *Capsella bursa-pastoris* in plant quality traits for insect herbivores. *Weed Research* 48:147–156.
- Kleijn, D., and W. J. Sutherland. 2003. How effective are European agri-environment schemes in conserving and promoting biodiversity? *Journal of Applied Ecology* 40:947–969.
- Kleijn, D., et al. 2006. Mixed biodiversity benefits of agri-environment schemes in five European countries. *Ecology Letters* 9:243–254.
- Leip, A., G. Marchi, R. Koeble, M. Kempen, W. Britz, and C. Li. 2008. Linking an economic model for European agriculture with a mechanistic model to estimate nitrogen and carbon losses from arable soils in Europe. *Biogeosciences* 5:73–94.
- Lewis, T. D., J. S. Rowan, C. Hawes, and B. M. McKenzie. 2013. Assessing the significance of soil erosion for arable weed seedbank diversity in agro-ecosystems. *Progress in Physical Geography* 37:622–641.
- Liu, J., L. You, M. Amini, M. Obersteiner, M. Herrero, A. J. B. Zehnder, and H. Yang. 2010. A high-resolution assessment on global nitrogen flows in cropland. *PNAS* 107:8035–8040.
- Lobell, D. B., K. G. Cassmann, and C. B. Field. 2009. Crop yield gaps: their importance, magnitude and causes. *Annual Review of Environment and Resources* 34:179–204.
- MacDonald, G. K., E. M. Bennett, P. A. Potter, and N. Ramankutty. 2011. Agronomic phosphorus imbalances across the world's croplands. *PNAS* 108:3086–3091.
- Marshall, E. J. P., T. M. West, and D. Kleijn. 2006. Impacts of an agri-environment field margin prescription on the flora and fauna of arable farmland in different landscapes. *Agriculture, Ecosystem and Environment* 113:36–44.
- Ngetich, K. F., J. Diels, C. A. Shisanya, J. N. Mugwe, M. Mucheru-Muna, and D. N. Mugendi. 2014. Effects of selected soil and water conservation techniques on runoff, sediment yield and maize productivity under sub-humid and semi-arid conditions in Kenya. *Catena* 121:288–296.
- Pelzer, E., et al. 2012. Assessing innovative cropping systems with DEXiPM, a qualitative multi-criteria assessment tool derived from DEXi. *Ecological Indicators* 18:171–182.
- Pimentel, D., et al. 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science* 267:1117–1123.
- Pywell, R. F., E. A. Warman, L. Hulmes, S. Hulmes, P. Nuttall, T. H. Sparks, C. N. R. Critchley, and A. Sherwood. 2006. Effectiveness of new agri-environment schemes in providing foraging resources for bumblebees in intensively farmed landscapes. *Biological Conservation* 129:192–206.
- Squire, G. R., C. Hawes, G. H. Begg, and M. W. Young. 2009. Cumulative impact of GM herbicide tolerant cropping on arable plants assessed through species-based and functional taxonomies. *Environmental Science and Pollution Research* 16:85–94.
- Squire, G. R., C. Hawes, T. A. Valentine, and M. W. Young. 2015. Degradation rate of soil function varies with trajectory of agricultural intensification. *Agriculture, Ecosystems and Environment* 202:160–167.
- Storkey, J., D. Brooks, A. Houghton, C. Hawes, B. Smith, and J. Holland. 2013. Using functional traits to quantify the value of plant communities to invertebrate ecosystem service providers in arable landscapes. *Journal of Ecology* 101:38–46.
- Tattersall, F. H., D. W. Macdonald, B. J. Hart, P. Johnson, W. Manley, and R. Feber. 2002. Is habitat linearity important for small mammal communities on farmland? *Journal of Applied Ecology* 39:643–652.
- Taylor, M. E., and M. D. Morecroft. 2009. Effects of agri-environment schemes in a long-term ecological time series. *Agriculture, Ecosystem and Environment* 130:9–15.
- Valentine, T. A., P. D. Hallett, K. Binnie, M. W. Young, G. R. Squire, C. Hawes, and A. G. Bengough. 2012. Soil strength and macropore volume limit root elongation rates in many UK agricultural soils. *Annals of Botany* 110:259–270.
- Verheijen, F. G. A., R. J. A. Jones, and R. J. Rickson. 2009. Tolerable versus actual soil erosion rates in Europe. *Earth-Science Reviews* 94:23–38.
- Vickery, J. A., N. Carter, and R. J. Fuller. 2002. The potential value of managed cereal field margins as foraging habitats for farmland birds in the UK. *Agriculture, Ecosystem and Environment* 89:41–52.
- Wood, R., M. Lenzen, C. Dey, and S. Lundie. 2006. A comparative study of some environmental impacts of conventional and organic farming in Australia. *Agricultural Systems* 89: 324–348.

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