TECHNICAL PAPER · VERSION 1.2 · 2026-11-27 · DOI 10.5281/ZENODO.24588634

What would it take to make arable farming nature-positive?

A satellite and GIS method to assess ecological outcomes, inform the design of arable cropping systems, and support natural-capital accounts and nature-related disclosure

How cropping systems are designed and how farms are laid out beyond the cropped fields shape what arable farming can contribute to nature recovery. This paper extends the EcoDynamics Diagnostic Engine (EDDE) to assess different cropping systems using satellite and GIS analysis. It draws on long-term experiments at Rothamsted and the Kellogg Biological Station alongside UK commercial examples. The comparisons span conventional tillage, long-established no-till, cover cropping with reduced or zero chemical inputs, organic continuous cover and diverse regenerative rotations.

The extension brings cropping-system diagnosis into EDDE's existing whole-farm assessment. Growers and advisers can assess current ecological performance, trace it back to 2018 and identify changes worth testing. The same assessment provides evidence of cropland ecosystem condition and change for natural-capital accounts and nature-related disclosure.

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Abstract

Harvest and cultivation interrupt ecological succession in arable fields. How much cover remains and how soon living roots return help determine the conditions for recovery. This study extends the EcoDynamics Diagnostic Engine (EDDE) to arable land, adding an arable method to its established assessments of grassland, moorland, woodland and forestry, and agroforestry. The arable-focused extension assesses the ecological outcomes of different cropping systems and informs their design.

The study uses satellite records from 2018 to 2025 and GIS analysis. Three long-term experimental areas at Rothamsted, Hertfordshire, set the cover references. The comparisons include 23 plots in a replicated experiment at the Kellogg Biological Station, Michigan, and four UK cases drawn from four commercial farms and the conventional example near Morley. The systems assessed span conventional tillage, long-established no-till, cover cropping under reduced or zero chemical inputs, organic continuous cover and diverse regenerative rotations.

We derived weekly spectral scores for green vegetation, crop residue and bare ground. We normalised two annual summaries against the Rothamsted references and combined them into a cover axis. The summaries were the annual mean weighted cover, which weights residue below living green cover, and the longest majority-bare run, the longest consecutive run of weeks with a bare score above 0.5. The cover axis informs the Water Cycle component of the EDDE's four-process composite, which also reflects energy flow, mineral cycling and the dynamics of living communities, each process scored against an ecoregion reference state. The results are presented as four-process composite scores for the Kellogg plots and cover-axis scores for the UK cases. The paper also describes the Version 1 mapping of the composite to the 1 to 9 Land Health Score, provisionally calibrated using the Morley and organic continuous-cover references, with the AHDB Soil Health Scorecard informing the choice

of anchor values. A separate check against sub-metre satellite imagery agreed on green versus non-green cover for 41 of 43 field samples on the autumn dates assessed.

At Kellogg, all 12 cover-cropped plots had higher eight-year median composite scores than all six conventionally tilled plots. Kellogg's no-till plots had a higher group median than the conventional-tillage plots, with overlapping scores. Among the UK cases, the organic continuous-cover farm scored highest on the cover axis, at 0.81. A long-established no-till operation and the conventional reference both scored 0.55 at the reported precision, and the diverse-rotation regenerative case scored 0.51. The seasonal profiles revealed phenological fingerprints for the systems studied, including differences in when signs of exposure were most pronounced.

The arable extension brings cropping-system diagnosis into EDDE's existing whole-farm assessment. It places the ecological performance of cropped fields in the context of hedgerows, margins, field sizes and the wider farm layout, and follows change through seasons and rotations. This gives growers and advisers a basis for choosing which ecological functions to strengthen and where changes to the cropping system could improve land health. Input use and productivity are among the outcomes they can investigate when testing those changes.

A proposed multi-farm trial would test how well the assessment transfers across farms and how the satellite estimates relate to independently measured soil function. Reported through its Land Health Score bands and underlying indicators, the assessment provides reference-based estimates of cropland condition and change that support natural-capital accounts and nature-related disclosure.

Keywords: arable land health, ecosystem condition, cover continuity, bare soil, remote sensing, fractional cover, cover indices, EcoDynamics Diagnostic Engine, Land Health Score, regenerative agriculture, no-till, outcome-based assessment, AHDB Soil Health Scorecard, Rothamsted, Kellogg Biological Station, natural-capital accounting, nature disclosure

Introduction

The EcoDynamics Diagnostic Engine (EDDE) uses satellite and GIS analysis to assess ecosystem condition across many fields and follow changes over time. It extends the Ecological Health Index, a field method that draws on Landscape Function Analysis (Xu et al., 2019; Link, 2026). EDDE examines the water cycle, energy flow, mineral cycling and the dynamics of the living community together and interprets them in light of the climate, terrain and ecology of each place. This paper extends the method to arable land and asks how an assessment of ecological function can inform the design of cropping systems.

The weekly record goes back to 2018 and helps identify which process may be limiting a field's recovery. EDDE uses that diagnosis to set priorities for individual fields under four management scenarios, including continuing current practice and pursuing different levels of improvement. The same field records can be brought together across a farm or a portfolio of farms. Dated evidence of ecosystem condition and change can inform UN SEEA natural-capital accounts and nature disclosures under frameworks such as the Taskforce on Nature-related Financial Disclosures (TNFD) and the European Sustainability Reporting Standards (ESRS).

Harvest removes the crop canopy, and cultivation can leave soil exposed until the next crop establishes. The question is how to give the field time to recover while keeping it in production. A grower can choose whether and when to plough, how much stubble to leave after harvest and when to drill the next crop. There may be time to establish a cover crop between two cash crops. A grass-clover ley may fit in a longer rotation. Hedges and margins shape the ecology of the farm as well. The assess-

ment begins with the cropped area, where satellite and GIS analysis can estimate how much living and protective cover a field carries through the year and how long signs of soil exposure persist.

Three long-term experimental areas at Rothamsted set the cover scale. The study examines how the assessment responds to different farming systems on 23 plots at the Kellogg Biological Station and in UK comparisons that include conventional, organic, regenerative and no-till approaches. Higher-resolution imagery provides a separate check on the greenness estimates.

A proposed multi-farm trial would build on this current Version 1 to test how closely the satellite estimates track physical ground cover and whether differences in cover can help explain independently measured differences in soil condition.

The ecology of arable cropping systems

Disturbance and succession

Harvest and cultivation keep arable fields in the early stages of ecological succession. As plants establish, they change the conditions in which other organisms live. The next harvest or cultivation interrupts that sequence. Looking to nature for examples of soil disturbance and ecosystem regeneration, we find that the balance of impact and rest determines whether ecosystems remain arrested at lower levels of successional dynamics and health or whether the impact can result in ecosystem regeneration to a higher level. For example, wild boar turn over soil and bury litter as they root. The open patches give seeds room to germinate. A review found gains as well as losses in nutrients and changes in soil communities (Barrios-Garcia and Ballari, 2012). In Swiss hardwood forests, matched rooted and unrooted plots differed in the mineral soil. Carbon, nitrogen and microbial biomass concentrations were higher in the rooted plots (Wirthner et al., 2012).

In a grassland experiment, simulated rooting increased plant diversity. Using five years of observed disturbance, the researchers projected that about 98.7 per cent of the grassland would remain undisturbed at equilibrium. After eight years, the vegetation in the rooted plots still differed from that in the controls (Horčičková et al., 2019). Most of the grassland retained its cover. The findings are consistent with recovery after a local disturbance, with differences still visible in the disturbed patches years later.

Tree-fall is another example in which a gap in the canopy of the surrounding forest opens. Plants establish in that opening, where regeneration can take years (Brokaw, 1985). On a wind-exposed strip, a patch can stay bare even as vegetation advances slowly from its edges (Watt, 1947). An opening can thus persist even where plants grow close by.

Under an unbroken sward, earthworms rebuild soil. Drought and frost interrupt their activity (Darwin, 1881). Floods can deposit sediment across large areas of vegetated floodplain (Junk et al., 1989). The size and intensity of a disturbance and how often it occurs help determine what remains and whether it has time to recover (Pickett and White, 1985).

A pattern that repeats without allowing sufficient recovery does not regenerate in ecological terms, whatever the practice is labelled as. Growers can influence how much soil they disturb and whether they leave cover in place. Their choice of crops and sowing dates affects when the field will next have living roots. Over several years, the rotation can give the soil periods under crops or leys in which to rebuild. The flora and fauna of the surrounding hedges, margins and other habitats are also part of the field's ecology.

Consider a ploughed field left bare through winter or during a fallow. The surface stays exposed and the soil goes without fresh inputs from living roots. The working hypothesis is that recovery after

cultivation depends in part on how soon living cover returns. The examples of natural disturbance help frame that question. The satellite method estimates cover at the field surface.

Tillage and the conditions for recovery

Growers manage disturbance through practices ranging from deep inversion ploughing to minimum tillage and no-till. Cultivation can break soil aggregates, expose readily decomposable carbon to oxidation and cut fungal networks. These changes can reset biological succession in the cultivated layer. Repeated deep cultivation can leave a compacted plough pan that restricts roots and drainage.

Growers till to terminate a crop or control weeds, prepare a warm, clean seedbed or work green manures and imported organic matter into the soil. In much no-till farming, growers use herbicides to terminate cover and clear weeds. A UK national survey found that black-grass resistance tracked the history of herbicide exposure (Hicks et al., 2018). The risk accompanies chemical termination under any tillage regime.

Reducing disturbance can lower erosion even on a field that still receives little fresh carbon from living roots. The yield response to less disturbance depends on climate. In a global meta-analysis of conservation agriculture, no-till reduced yields on average in rainfed humid conditions across the residue and rotation groups. The significant yield advantage from combining no-till with residue retention and diverse rotations appeared in rainfed dry conditions (Pittelkow et al., 2015).

In 92 comparisons based on equal masses of soil, no-till held on average 6.7 per cent more carbon in the upper 30 centimetres than inversion tillage. For the 35 pairs with crop-input data, differences in carbon input accounted for about 30 per cent of the variation in soil-carbon stock differences between the paired plots. Most of the variation remained unexplained. Each pair was defined by a tillage contrast, so the crop-input analysis could not rank the independent effects of cover and tillage (Virto et al., 2012).

The amount of carbon near the surface can rise as carbon decreases deeper in the soil. Across 69 paired experiments with samples below 40 centimetres, the pooled no-till effect was 3.15 tonnes more carbon per hectare in the upper 10 centimetres and 3.30 tonnes less per hectare at 20 to 40 centimetres. The only significant gain across the upper 40 centimetres was under double cropping (Luo, Wang and Sun, 2010). Where some of the change reflects redistribution, shallow sampling can overstate the gain (Baker et al., 2007).

Periodic cultivation can reduce the gain near the surface. That limits the mitigation potential of no-till on its own, even where it brings other benefits for soil quality (Powlson et al., 2014). The response across the soil profile also depends on soil and climate. On cool, moist sandy soils, one analysis estimated a gain of 0.35 tonnes of carbon per hectare per year over 20 years (Ogle et al., 2019).

Living roots, canopy and crop residue

Living plants feed the soil community. Their leaves fix carbon through photosynthesis, and their roots release some of it into the soil as exudates. As fine roots die and are replaced, they supply more fresh carbon. Microbes and mycorrhizal fungi use these inputs and help bind soil particles into aggregates and cycle nutrients.

Carbon from roots tends to remain in the soil longer than carbon from shoots. In the long-term Ultuna experiment, the fitted humification coefficient was about 2.3 times as high for root carbon as for above-ground residue. The coefficient represents the share of an input retained as soil organic matter. Root inputs were estimated (Kätterer et al., 2011). In a small set of comparisons with complete

data for both sources, the mean residence time of root carbon was about 2.4 times as long as that of shoot carbon (Rasse et al., 2005).

A crop canopy and the residues left after harvest intercept raindrops and help protect the surface from erosion. Residue shades and insulates the soil, slows evaporation and releases carbon as it decomposes. A living crop can protect the surface as its roots supply fresh carbon below it.

When the ground stays bare

A long period without living roots cuts off the supply of fresh root carbon. Where the ground also lacks a protective layer of residue, rain can break up soil aggregates and form a surface crust. Water that would otherwise soak in can run off, carrying sediment and the nutrients bound to it into watercourses. Exposed organic matter is vulnerable to loss. The size of each effect depends on the soil, slope, weather and length of exposure.

Montgomery (2007) compiled 1,673 erosion values from 201 studies. Among 39 paired comparisons of tilled and no-till ground, the median difference in erosion rate was twentyfold. Among 46 pairs comparing cultivated ground with native vegetation, it was eighteenfold. The studies compared whole systems and leave open how much of the difference came from cover and how much from other features of the treatments.

In experiments on a Pullman clay loam, increasing the amount of surface crop residue reduced the initial rate of soil evaporation (Steiner, 1989). In a four-year dryland maize and soybean experiment in eastern Nebraska, residue lowered maximum surface soil temperature by at least five degrees Celsius (Power, Wilhelm and Doran, 1986). Living plants can cool a surface as they transpire. Dead residue shades and insulates it. Water evaporates from wet bare soil too. Local weather, soil moisture and texture all influence surface temperature.

At field scale, the amount of rain that infiltrates and the rate at which the soil dries are relevant to resilience to floods and drought. The Water Cycle score uses indicators of bare soil, litter, erosion risk and terrain hydrology. Of the four process scores, it is the one on which cover has most influence (Link, 2026). It describes surface conditions relevant to runoff and erosion. Flood peaks and water quality require separate measurements.

In humid temperate cropland, a long bare period is the clearest sign of degradation visible at the surface. Biological decomposition can continue through much of the year, though cold and seasonal dryness can slow it in Michigan and the UK. A bare week describes the surface at that time. Estimating net carbon loss requires evidence of what happens to the carbon over a longer period.

Holistic Management places such climates at the less brittle end of a qualitative scale from 1 to 10. Moisture and biological activity are spread more widely through the year, and bare ground between plants is harder to maintain. Towards the brittle end, dead material can remain standing and oxidise (Butterfield et al., 2019). EDDE uses rainfall variability and the seasonal water balance to place a climate on this scale (Link, 2026). The result places the climate within that framework and is not a measurement of decomposition.



Photographs © M J Richardson (bare soil, living cover; the same field two months apart) and Brian Robert Marshall (crop residue), CC-BY-SA 2.0, via Geograph.

Figure 1. The three surface states the scoring distinguishes, for illustration: bare soil, living cover and crop residue. The bare-soil and living-cover panels are the same field two months apart. Photographs via Geograph under the Creative Commons Attribution-ShareAlike 2.0 licence (creativecommons.org/licenses/by-sa/2.0/), cropped to a common aspect: bare soil, 'Newly ploughed field near Nether Falla', and living cover, 'Barley field at Nether Falla' (a spring-barley nurse crop), both by M J Richardson (geograph.org.uk/photo/4934851 and geograph.org.uk/photo/5023088); crop residue, 'Wheat stubble, near the Firs, Beckhampton', by Brian Robert Marshall (geograph.org.uk/photo/962446).

Cover between crops and through the rotation

Within a cropping year, growers can keep living roots in the soil for longer by sowing cover crops, growing companion crops or establishing an under-sown crop before the main crop is harvested. The practitioner soil-health literature recommends keeping living roots in the ground for as much of the year as possible (Brown, 2018). Compost and woodchip can add organic material alongside the inputs from roots.

A rotation gives a grower several years in which to plan for recovery. Alternating cash crops, break crops, legumes, leys and fallows brings different demands on the field and helps interrupt pest, disease and weed cycles. A ley, a temporary sward in the rotation, can rebuild soil structure and increase soil carbon. A ley that includes legumes can also add nitrogen, and deep-rooting species can penetrate a compacted layer. A field whose fertility and structure have declined under successive cash crops needs a phase in which they can rebuild.

In a meta-analysis of 122 studies, rotations had about 3.6 per cent higher total soil carbon concentration and about 21 per cent higher microbial biomass carbon than monocultures. Rotations with a cover crop had about 8 per cent higher total soil carbon concentration than monocultures. Nearly all the cover crops in that subgroup were legumes, which leaves open what cover alone would add to an otherwise identical rotation (McDaniel, Tiemann and Grandy, 2014). Crop diversification more broadly showed no average yield penalty, though results varied with the practice and setting (Tamburini et al., 2020).

In the Woburn ley-arable experiment, soil organic carbon in the upper 25 centimetres rose from about 0.98 to 1.23 per cent over 28 years in a rotation with a three-year grazed grass-clover ley. A mostly cereal, all-arable treatment ended near 0.94 per cent after 70 years. The modelled balance showed that much of the new carbon added over time was lost even under leys. The calculation concerns those new inputs. Any loss from the original stock would be a separate quantity (Johnston et al., 2017).

Table 1 sets out how the main management approaches can affect the field and what cover signal the satellite assessment might pick up.

Table 1. How each management approach changes the field, the ecological response expected from the literature and the cover signal likely to appear in satellite imagery.

APPROACH	ECOLOGICAL ACTION	MECHANISM EXPECTED FROM THE LITERATURE	EXPECTED SATELLITE SIGNAL
Conventional (plough plus synthetic inputs; bare over winter or in fallow)	Baseline; long bare windows expose the surface and reduce fresh-carbon input	Erosion and evaporation rise with exposure; fresh-root input falls (Montgomery, 2007; Steiner, 1989)	Low protective cover and long bare-soil runs
No-till or conservation tillage without added cover	Removes the cultivation impact; persistent bare or stubble windows add little living input	Herbicide history is associated with black-grass resistance (Hicks et al., 2018); near-surface carbon may rise without reliable whole-profile gain (Baker et al., 2007; Luo et al., 2010)	Protective cover close to conventional; bare runs persist
Cover cropping, companion and under-sown crops, continuous living cover	Adds living-root and canopy input	Root-derived carbon is preferentially retained (Kätterer et al., 2011; Rasse et al., 2005)	Higher protective cover and shorter bare runs
Diverse rotations with leys, including organic systems	Year-round cover, legume nitrogen, the ley rest phase; temporal diversity	Rotations and leys build carbon and nitrogen over years (McDaniel et al., 2014; Johnston et al., 2017)	Sustained high cover plus the multi-year trend
Integrated grazing livestock on leys and cover	Converts leys and cover; dung and urine cycle nutrients	Grazing outcomes depend on timing, intensity and recovery	Cover from leys plus the soil-carbon trend

A field left bare for a season and a field resting under a cover crop, green manure or herbal ley can both be described as fallow. In the first, the surface remains exposed. In the second, cover can protect the surface while the soil rebuilds. Estimates of how much cover a field holds and how long signs of exposure persist give the method a way to distinguish those cases.

The controlled Kellogg comparison examines cover within annual cropping systems and includes no ley treatment. A ley-arable trial would test the effect of the rotation directly. EDDE treats regeneration as a trend over several years. The mineral and community scores are intended to respond over roughly three to ten years. The cover estimate can respond sooner.

Diversity within and beyond the field

Hedges, trees, margins and other uncropped strips provide habitat for the wider farmland community and can help regulate pests. Even a field with rich margins can leave its soil exposed. The design of a cropping system therefore concerns the cropped surface and what surrounds it.

A diverse rotation changes the habitat available from one year to the next. The arrangement of fields, woods and margins shapes what is available across the farm (Benton et al., 2003; Tscharntke et al., 2005). Together, the sequence of crops and the distribution of habitats may help explain how well arable land recovers.

The arable cover score is built from two inputs, the annual weighted-cover summary and the longest majority-bare run. It does not take hedgerows, trees, habitat structure or land-cover diversity as

inputs. EDDE's whole-farm assessment reports hedgerow and tree-line extent, habitat structure, land-cover diversity and landscape position; these are not folded into the field-level cover score.

What a practice label can tell us

Regenerative, conservation, no-till and organic are familiar labels to growers and buyers. They vary in what they specify about management. A review of 229 scholarly articles and 25 practitioner organisations found no agreed definition of regenerative agriculture. Of the articles, 22 offered an approximate definition, 99 a description and 108 neither. The authors drew attention to the difficulties this poses for certification and payment schemes that attach value to the word (Newton et al., 2020).

The Ecological Health Index that EDDE extends records what can be observed on the ground, including bare soil, litter and plant functional groups (Xu et al., 2019). The grazing literature offers examples of the distinction between a named approach and a measured outcome. Teague and Barnes (2017) describe adaptive multi-paddock grazing. Hawkins (2017) compared Holistic Planned Grazing with continuous grazing and found no significant mean differences in plant basal cover, plant biomass or animal gain. The responses varied between studies. The farming systems in this paper are described by what growers do and by what can be observed or estimated in their fields.

Cultivated fields can keep substantial cover and score highly for it. Examples include organic systems with leys and cover, and experimental systems that combine tillage with cover crops. A no-till field can still stay exposed for a long period between crops. The multi-farm trial would test whether arable fields more widely fall along a continuum of cover across tillage categories.

Why the method starts with cover

Soil carbon is often the outcome a buyer asks about. The stock reflects both inputs and losses. How long it takes to detect a change depends on the size of the change and the precision of sampling. In a modelling study of increased carbon inputs, about 3 per cent was the smallest change in the stock that the sampling design could detect. Detection at 90 per cent confidence took six to ten years. With a coarser threshold of 15 per cent, the change was undetectable (Smith, 2004).

Cover changes more quickly. A field with living roots through more of the year can supply fresh carbon for longer, while canopy or residue can protect the surface as the next crop establishes. Successive satellite observations allow the method to follow changes in cover.

Satellite and GIS assessment

Mapped field boundaries define the area assessed. For each field, the method uses Sentinel-2 images to build a weekly record of green, residue and bare scores. It fills and flags weeks when no usable image is available. Once the field boundaries and processing are in place, the same archive and procedure can be used to assess another field or year at low additional cost.

Two summaries describe each field over a calendar year. The annual mean weighted cover summarises how much cover the weekly scores indicate. The longest majority-bare run records how long the bare score stayed above a threshold. The method uses three scales in sequence. First, the method normalises both summaries against the Rothamsted references and combines them into a cover axis on a scale from 0 to 1. Second, the cover axis is the leading input to the EcoDynamics Diagnostic Engine (EDDE) assessment of four ecosystem processes, each scored from 0 to 100 against the field's ecoregion reference state and combined into a four-process composite on the same 0 to 100 scale. Third, the arable method maps that composite to a provisional 1 to 9 Land Health Score. Link (2026) describes the engine, its reference-state scoring and the EcoDynamic Index time series.

Standing stubble helps explain why both summaries are needed. A field under dry stubble can have a positive residue score and a bare score above 0.5 in the same week. The stubble protects the soil even though the bare score is high enough to flag possible exposure. The annual mean takes account of the residue. The longest run records how long the bare score stayed above 0.5.

Weekly spectral scores

The method derives three weekly spectral scores for each field from Sentinel-2 surface reflectance: a green score from the modified soil-adjusted vegetation index MSAVI2, which uses the near-infrared and red bands B8 and B4 (Qi et al., 1994); a residue score from a normalised difference of the two shortwave-infrared bands B11 and B12 (Van Deventer et al., 1997; Daughtry et al., 2004); and a bare score. These public indices inform the three normalised weekly scores for green, residue and bare cover, following standard fractional-cover practice (Guerschman et al., 2009, 2015); the exact construction is part of the proprietary implementation.

Sentinel-2 has four bands at a native resolution of 10 metres. Its two shortwave-infrared bands have a native resolution of 20 metres. The nominal revisit at the same viewing angle is about five days. Cloud, snow and shadow determine which scenes can be used.

The green signal was previously scaled from the normalised difference vegetation index (NDVI). MSAVI2 reduces sensitivity to the soil background and to saturation under dense canopy. The change lowered the green scores and raised the bare scores.

Fractional-cover studies have long used green vegetation, residue and bare soil to describe the surface. Spectral-mixture methods estimate the physical share of each component from reference spectra (Roberts et al., 1998; Asner and Lobell, 2000; Guerschman et al., 2009, 2015). In this method the three scores are normalised spectral indices. The difference between the two shortwave-infrared bands helps identify residue (Van Deventer et al., 1997; Daughtry et al., 2004). Moisture affects how well that difference distinguishes residue from soil (Quemada and Daughtry, 2016). Sentinel-2 lacks the narrower shortwave bands best suited to separating them (Daughtry et al., 2004; Dennison et al., 2023). Sparse, low-biomass living cover can also be hard to distinguish from bare ground.

The accuracy of spectral-mixture estimates does not establish the accuracy of these indices. The proposed trial would compare the satellite estimates with physical ground cover, including wet cereal stubble. Where the spectral-index retrieval is unavailable, the method uses the older bare-soil and greenness signals.

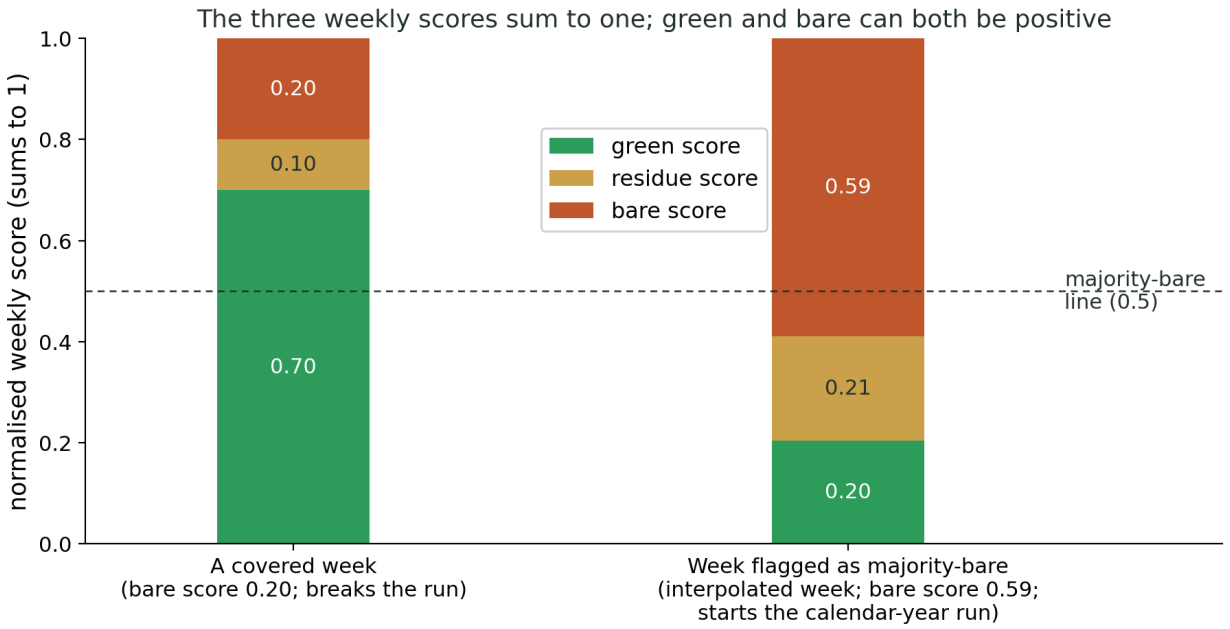


Figure 2. The three weekly scores sum to one. Two example weeks show that living green and bare can both be positive, and that a week counts as majority-bare only when the normalised bare score exceeds 0.5.

Observed and gap-filled weeks

Table 2 gives the rules for screening images, grouping them into weeks and filling gaps. An observed week has at least one accepted Sentinel-2 scene. When there is no usable scene, the method estimates cover from the nearest observed weeks on either side. The longer the gap, the closer the estimate moves towards the seasonal baseline. If an observation is available on just one side, its influence decreases with distance. If there are no observations on either side, the estimate takes the baseline value. The method completes the calendar year without imposing a maximum gap length.

Table 2. How the method screens observations and uses them to calculate the annual cover summaries.

STEP	RULE
Imagery product	Copernicus Sentinel-2 Level-2A surface reflectance (collection S2_SR_HARMONIZED). The visible and near-infrared bands have a native resolution of 10 metres and the two shortwave-infrared bands a resolution of 20 metres. Scenes are screened using Cloud Score Plus and the per-scene cloud fraction within the region of interest.
Signals	Three weekly spectral scores: green from a soil-adjusted greenness index (MSAVI2; Qi et al., 1994) on the near-infrared and red bands B8 and B4; residue from a normalised difference of the two shortwave-infrared bands B11 and B12 (Van Deventer et al., 1997; Daughtry et al., 2004); and a bare score, including for filled weeks. The three are combined into a normalised weekly triple that sums to one, following standard fractional-cover practice (Guerschman et al., 2009, 2015).
Screening	Scenes are screened for cloud, snow and shadow. Only scenes in the accepted usability classes enter a week (Prime Quality, Haze Risk, Clear Slot, Off-Nadir).

STEP	RULE
Weekly aggregation	The method averages accepted scenes within each calendar week using a region mean at 10 metres. The prairie-strip reconstruction buffered the plot interior (see Results).
Majority-bare	A week counts as majority-bare when its normalised bare score is strictly above one half. The total majority-bare weeks and the longest consecutive run are reported separately.
Gaps	For weeks with no accepted scene, the method interpolates between the nearest observed weeks on either side. It gives more weight to the seasonal baseline as the gap length increases. If observations are available on one side only, the result moves towards the baseline with distance from that observation. If neither side has an observation, the week takes the baseline. The calculation fills gaps to complete the 52-week series. The main analysis retained plot-years with fewer than 20 directly observed weeks.
Fallback	In a filled week, where a sharp drop in Sentinel-1 radar backscatter contradicts a rise in interpolated greenness, the method damps the greenness and marks the week as a Sentinel-1 fallback. Other filled weeks are marked as plain interpolation.
Year boundary	The calendar year is the analytical unit. A bare run ends at 31 December for the purpose of scoring.
Counts	The result records counts of valid, filled and fallback weeks, and the years included in each plot or field median.

The seasonal baseline can matter when there is a gap in winter. In a period with little cover, the baseline can pull the estimate down far enough for the bare score to exceed 0.5. This can extend the apparent bare run. The calculation is the same in observed and gap-filled weeks. In a filled week, the weekly scores are formed from the interpolated signals in the same way as for an observed week. The record distinguishes plain interpolation from weeks when a drop in Sentinel-1 radar return dampens the interpolated greenness. Sentinel-1 enters the cover calculation at this gap-filling step. Using radar to corroborate cover through cloud is still in development.

Two annual summaries

The completed 52-week series yields two summaries for each field and year.

- **Annual mean weighted cover.** The method combines the green and residue scores into a weekly weighted cover score, giving residue less weight than living cover, then averages over the year. Crop residue protects the soil surface. Living cover also supplies fresh carbon through its roots.
- **Longest majority-bare run.** This is the longest stretch of consecutive weeks with a normalised bare score strictly above 0.5. A score of 0.5 or less ends the run. The calculation uses weeks from a single calendar year. The total majority-bare weeks and the duration of the longest uninterrupted run are reported separately.

Changing the order of the weeks would leave mean weighted cover unchanged. The longest run depends on the order of both observed and filled weeks. It indicates how long possible exposure per-

sisted. Cultivation, cutting and grazing can each cause a short disturbance that the method does not measure directly.

How Rothamsted sets the cover-axis scale

Each annual summary is normalised to a scale from 0 to 1 using the Rothamsted references. The two normalised summaries form the cover axis. The calculation uses spectral scores and reference endpoints and is independent of management and brand labels. The Kellogg trial and the commercial farms were assessed on the same axis. They provide evidence of how it responds beyond the Rothamsted areas that set its endpoints.

The lower Rothamsted cover reference is the mean of two arable experimental references in the English lowlands. The electronic Rothamsted Archive publishes the centre points of the experiment areas. In the absence of published vector boundaries, the reference footprints were drawn using those points.

At Broadbalk, weighted cover within the 3.02-hectare footprint was about 0.25 and the longest majority-bare run was about 28 weeks. At Hoosfield, the continuous spring barley area was represented by a 1.74-hectare box centred on the archive point. Its individual treatment plots are smaller than a pixel. Weighted cover was about 0.25 and the longest run was about 25 weeks. Across 2018 to 2025, the two areas gave a lower Rothamsted cover reference of about 0.25 and a run of around 27 weeks. This reference represents an arable area with a growing season and a long period of estimated exposure.

Park Grass sets the high-cover endpoint. The 3.67-hectare area comprises the roughly 2.8-hectare permanent hay meadow experiment and surrounding permanent grass of the same cover type. Weighted cover was about 0.48 and the longest majority-bare run was about five weeks. The commercial organic continuous-cover farm is used later in the calculation to anchor the provisional Land Health Score.

Published accounts give the extent of the Broadbalk experiment as about 4.8 hectares (Stroud et al., 2024). The footprint traced for this assessment covers 3.02 hectares. The boundaries were defined differently, so area alone cannot tell us which sections of the experiment the traced footprint includes. An exploratory reconstruction of the Broadbalk sections is described in Appendix A.

From the cover axis to the Land Health Score

The cover axis is the input to the Water Cycle. Productivity feeds into Energy Flow, the mineral term into the Mineral Cycle and the community term into Community Dynamics. After Rothamsted normalisation, the method scores each process against the field's ecoregion reference state. The scale runs from 0 to 100 per cent, from a degrading to a superior archetype.

Cover carries the largest weight in the composite, followed by productivity, then the mineral and community terms. The engine's limiting-process rule draws the composite towards the weakest living axis.

In the general EDDE method, the year's peak weekly EcoDynamic Index determines the annual Land Health Score. For arable fields, the score comes from the four-process field-year composite, which uses a whole year's cover record.

The provisional 1 to 9 Land Health Score uses the two-point procedure applied to moorland: a linear mapping anchored on the conventional Morley-area reference and the organic continuous-cover reference. The conventional anchor is provisional because the reference's patch management is unverified. Band names run from 1, Collapsed, to 9, Flourishing. The score for an annual system can range from 1 to 8. Band 9 is reserved for near-natural land.

The AHDB Soil Health Scorecard benchmarks individual soil indicators, including soil organic matter by soil type and rainfall (AHDB, 2022). EcoIntel used AHDB's "Review" category to guide the placement of the Morley-area reference and the "Typical" soil organic matter range within "Monitor" to guide the placement of the organic continuous-cover reference. Neither reference had a measured scorecard result.

The provisional mapping rests on one reference per class. This paper describes the method and its inputs in outline. It does not reproduce the exact spectral-index construction, the process weighting, the calibration constants or a worked field-by-field calculation; the engine's ensemble coefficients, process weights and band-anchor constants are proprietary.

The 1 to 9 scale allows arable, grassland, moorland, woodland and forestry, and agroforestry on a mixed holding to be reported together, and the arable method joins EDDE's established assessments for those land types on one scale. The method extends the logic of the field-based Ecological Health Index (Xu et al., 2019), which scores observable ground indicators. For the arable assessment, the satellite record supplies the cover evidence and the two-point mapping places the score in a provisional band.

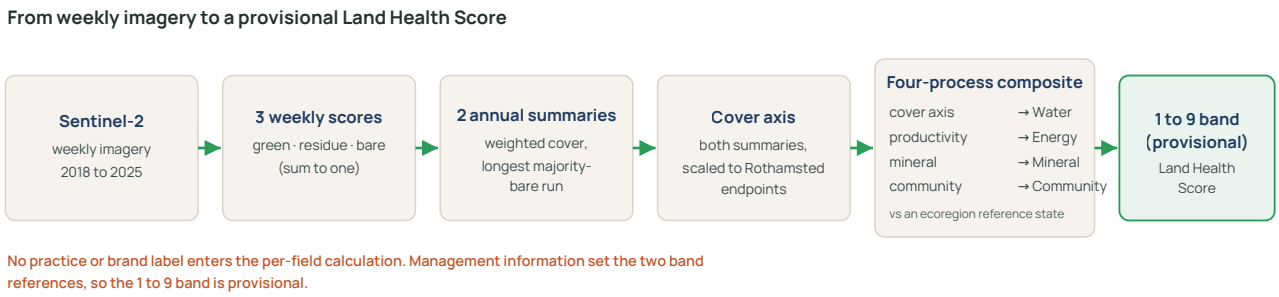


Figure 3. From weekly imagery to a provisional Land Health Score. Sentinel-2 images give three weekly scores, which reduce to two annual summaries and the cover axis scaled to the Rothamsted endpoints. The cover axis is the leading input to the four-process composite, with productivity, a mineral component and a community component at lesser weights, which maps to the provisional 1 to 9 band. The per-field calculation uses no practice or brand label; management information set the two band references.

Results

At Kellogg, each plot is represented by the median of its eight annual composite scores. The UK comparisons use case medians on the cover axis. The autumn imagery check uses separate images to test how well the weekly estimates distinguish green from non-green ground.

The Kellogg treatment comparison

The Main Cropping System Experiment at the Kellogg Biological Station Long-Term Ecological Research site in Michigan assigns farming systems at random to plots within replicated blocks. The plots share a climate and regional soil setting, with the Kalamazoo and Oshtemo soil series intermingled across the site. Rain falls throughout the year, and biological decomposition continues through most of the year. On the brittleness scale described above, Kellogg and the UK comparison sites fall towards the less brittle end of the scale.

The four farming systems use an annual rotation of maize, soybean and wheat. The treatments are conventional tillage (T1), no-till (T2), reduced-input management with a leguminous winter cover crop (T3) and biologically based management with zero chemical input and a leguminous cover crop (T4). The treatment labels have been stable since 1989. Each system had six replicate plots of about one

hectare, large enough for the method to score from Sentinel-2 imagery. One no-till plot (T2 R5) was accidentally ploughed in 1994 and recoded. Its exclusion leaves five no-till plots and 23 plots in all.

Eight years of plot scores

We recalculated the four-process composite for each plot and calendar year from 2018 to 2025 from the stored inputs, in a separate internal scoring run. Each plot is represented here by the median of its eight annual composite scores, on the 0 to 100 four-process composite scale.

All 12 cover-cropped plots scored above every conventional-tillage and no-till plot. The lowest cover-cropped median was 46.8 (KBS21), the highest conventional-tillage median was 36.2 (KBS06) and the highest no-till median was 42.0 (KBS09). The 10.6-point gap is the separation between the cover-cropped and conventional-tillage groups; the highest no-till plot falls within that interval. The area under the receiver operating characteristic curve (AUC) for the cover-cropped versus conventional-tillage comparison was 1.000.

In each of the six matched blocks, the reduced-input plot scored above its biologically based counterpart. The differences were 4.6, 1.5, 3.9, 8.3, 0.5 and 9.1 composite points. When the six reduced-input plots were compared as a group with the six biologically based plots, the AUC was 0.833.

The no-till scores were closer to the conventional scores than to those of the cover-cropped systems. The median was 34.7 for no-till and 29.3 for conventional tillage, a difference of 5.4 points between group medians. The plot scores overlapped. No-till scored higher in 26 of the 30 possible comparisons between the five no-till and six conventional plots (AUC 0.867).

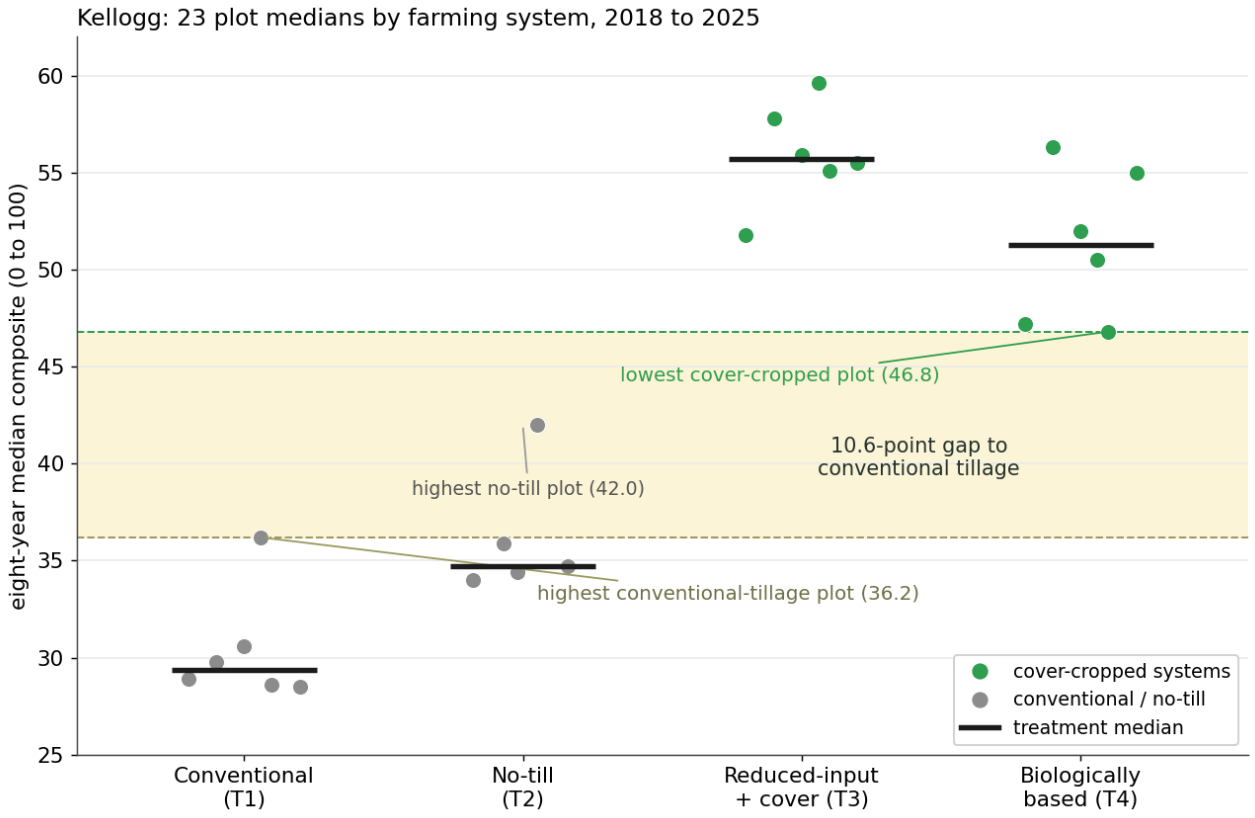


Figure 4. Eight-year median composite scores for the 23 Kellogg plots. All 12 cover-cropped plots scored above every conventional-tillage and no-till plot. The shading marks the 10.6-point gap between the lowest cover-cropped median (46.8) and the highest conventional-tillage median (36.2). The highest no-till median was 42.0.

Observation coverage and the influence of individual years

Across 184 plot-years, the median number of weeks with a direct optical observation was 23, with a range of 16 to 31. All 23 plot-years with fewer than 20 directly observed weeks fell in 2019.

The analysis repeated the comparison eight times, leaving out one calendar year each time. The cover-cropped plots still all scored above the conventional plots (AUC 1.000 in every comparison). The smallest margin was 3.9 points when 2020 was left out. The largest was 17.1 points when 2023 was left out. Omitting 2019 left a separation margin of 13.7 points.

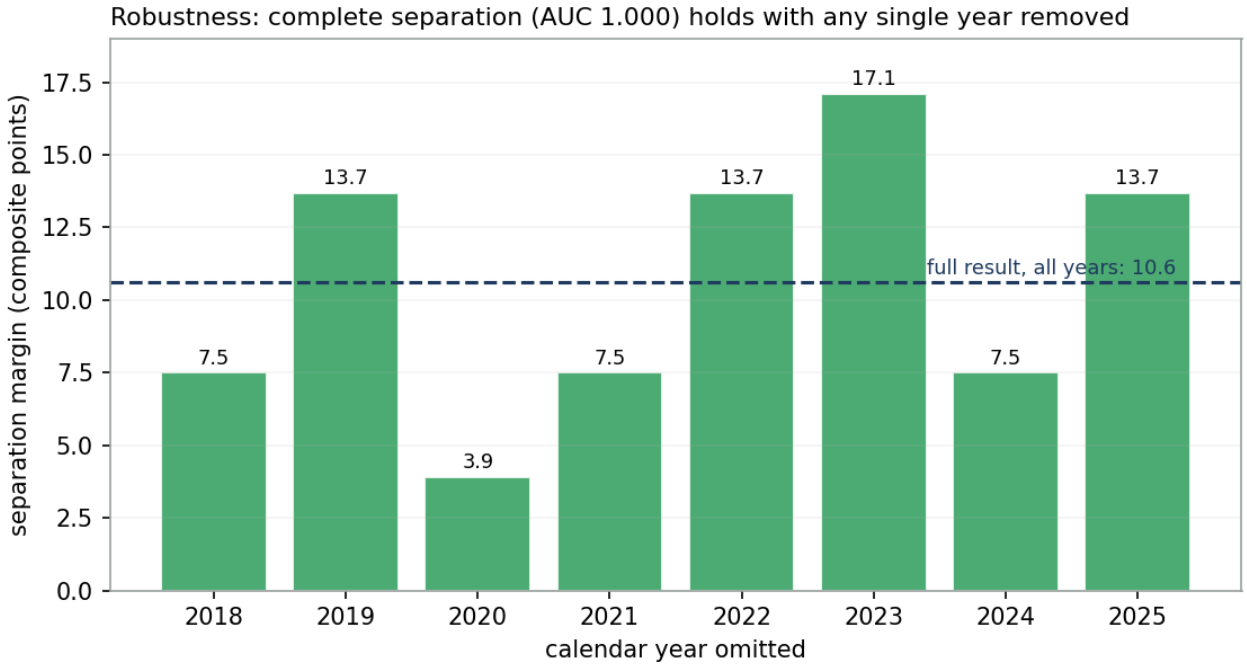


Figure 5. The separation survives dropping any single year. Omitting each year in turn from 2018 to 2025 leaves the cover-cropped and conventional plots fully separated, with margins from 3.9 to 17.1 points (every case gives an AUC of 1.000).

Testing the influence of the prairie strip

In April 2019, a permanent prairie strip was planted down the centre of every reduced-input and biologically based plot. The strip was about 4.5 metres wide and occupied roughly 5 per cent of each plot's crop area (Kemmerling et al., 2022). The whole-plot composite includes this permanent vegetation from 2019 onwards, so the strip could explain part of the difference between the cover-cropped and conventional plots.

The groups still separated when the strip was masked in a separate satellite-only reconstruction. With either mask, every cover-cropped plot median exceeded every conventional plot median over the seven years from 2019 to 2025 (Table 3).

Table 3. Separation between the cover-cropped and conventional plots by calculation geometry and period. The margin is the gap, in composite points, between the lowest cover-cropped plot median and the highest conventional plot median; composite scores run from 0 to 100. The full arable calculation (four-process composite) covers eight complete calendar years, 2018 to 2025. The prairie strip was planted in April 2019. The baseline with the strip retained covers 2018 to 2025, and the masked comparisons cover 2019 to 2025. The pre-strip row shows 2018 alone. The satellite-only margins are separate checks.

CALCULATION	GEOMETRY OR PERIOD	SEPARATION MARGIN
Full arable calculation (four-process composite)	Whole plots, 2018 to 2025	10.6 points (AUC 1.000)
Satellite-only reconstruction, baseline	Interior plots, strip retained, 2018 to 2025	14.0 points
Satellite-only reconstruction	Central strip column masked, 2019 to 2025	10.90 points (AUC 1.000)
Satellite-only reconstruction	Three central pixel columns masked, 2019 to 2025	10.85 points
Pre-strip check	2018 alone, strip-masked	AUC 0.819

The masks were aligned with the published plot boundaries. The reconstruction also excluded a buffer inside the plot edges before scoring. The shortwave-infrared bands have a native resolution of 20 metres. Grid alignment and resampling can spread the signal from a narrow strip across more than one output column. The analysis therefore tested masks of one and three central columns. After masking, each cover-cropped plot had 48 to 54 cells at 10 metres.

With one column masked, the gap between the lowest cover-cropped median (47.75) and the highest conventional median (36.85) was 10.90 points (AUC 1.000). The six reduced-input medians were 57.25, 58.35, 59.55, 60.10, 61.45 and 62.05. The six biologically based medians were 47.75, 55.40, 55.70, 57.80, 58.15 and 59.20.

Over 2018 to 2025, the full calculation gave a separation margin of 10.6 points for the whole plots. The satellite-only reconstruction gave a margin of 14.0 points for buffered plot interiors with the prairie strip retained. The calculations differed in both the area scored and the scoring procedure. The reconstruction omits the radar and gap-filling inputs used in the full calculation.

The masked comparisons start in 2019, so the difference from the strip-retained baseline reflects both the mask and the years included. The comparison of the two mask widths uses the same period and the same scoring procedure: widening the mask from one column to three reduced the margin by 0.05 points, from 10.90 to 10.85. The strip-retained baseline (2018 to 2025) and the masked comparisons (2019 to 2025) cover different periods and are reported separately.

In the masked comparisons for individual years, the plots separated completely in 2019, 2020, 2022, 2023 and 2025 (AUC 1.000). Separation was partial in 2021 (0.917) and 2024 (0.882). Applying the same mask in 2018, the only fully pre-strip year, gave an AUC of 0.819. The cover-cropped systems were already in place by then. Weather, crop phase, gaps in observations and establishment effects could each have contributed to the weaker result that year. The complete separation under the mask refers to the plot medians over 2019 to 2025.

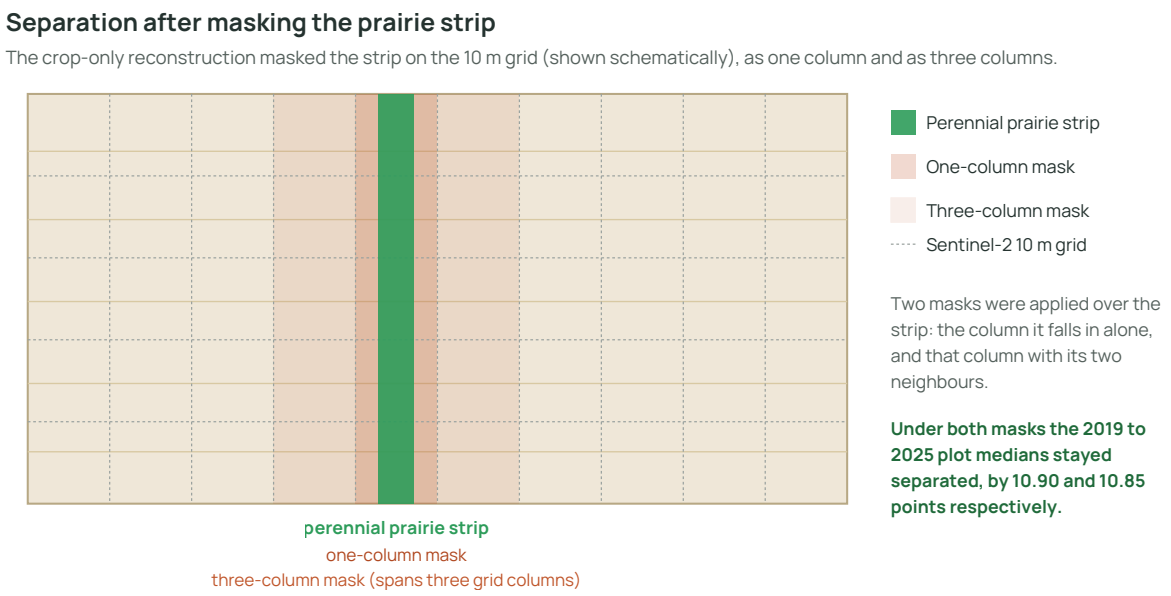


Figure 6. Separation after masking the prairie strip. The crop-only reconstruction masked the strip on the 10 m output grid (shown schematically), as one column and as three columns. Under both masks, the 2019 to 2025 plot medians stayed separated, by 10.90 and 10.85 points respectively.

How the components differed

Figure 7 compares the cover axis with the modelled soil-carbon input to the Mineral Cycle. On the cover axis, the reduced-input and biologically based systems scored about 0.50 and 0.41, and conventional tillage and no-till scored about 0.15 and 0.19. The modelled soil-carbon input ranged from about 0.75 to 0.79, a spread about one-ninth of that on the cover axis.

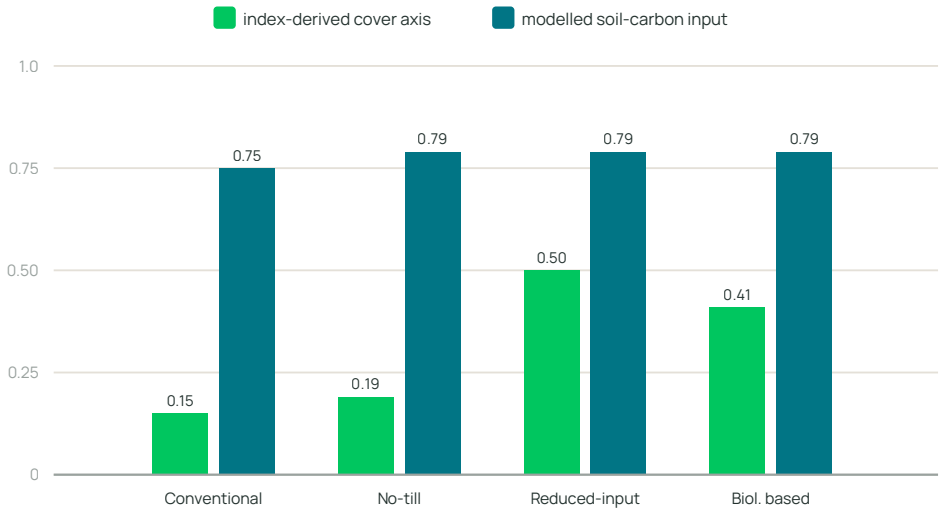


Figure 7. The cover axis and the normalised modelled soil-carbon input to the Mineral Cycle at Kellogg. For each treatment, the figure shows the median of the 2018 to 2025 plot medians. The cover axis combines two annual summaries derived from the weekly spectral scores and is a normalised score, not a physical cover fraction. The values shown are treatment medians; individual plots span a wider range, reported in the text.

The weekly scores show how the cover axis distinguished the groups. With the soil-adjusted green index, the mean green scores were close together. They were about 0.23 for conventional tillage, 0.24

for no-till, 0.25 for the biologically based system and 0.27 for the reduced-input system. The mean bare score was about 0.61 for conventional tillage and ranged from 0.53 to 0.56 in the cover-cropped systems. Higher weighted cover and lower bare scores account for the separation on the cover axis. Mean residue scores varied little, ranging from about 0.17 to 0.20 across the four systems.

The cover-cropped systems scored higher on weighted cover than conventional tillage under each residue weighting tested. Conventional tillage also had a longer run of majority-bare weeks at each of the thresholds tested, 0.4, 0.5 and 0.6.

The coefficient of variation in weekly greenness was highest under conventional tillage, at about 0.45, and lowest in the biologically based system, at about 0.39. These coefficients describe how much the signal varied over time.

Cover contributes most of the between-group difference in the composite, with productivity a smaller contribution and the mineral and community terms little. The final composite also adjusts for the weakest process, so the 10.6-point margin between the extreme plot medians is not a simple sum of the component contributions.

Cover and productivity each ranked every cover-cropped plot above every conventional plot (AUC 1.000 for each). The AUC was about 0.785 for the normalised modelled soil-carbon input to the Mineral Cycle and 0.507 for the input to Community Dynamics.

Limits of the comparison

Across individual plots, the cover axis ranged from about 0.13 to 0.21 under conventional tillage, 0.18 to 0.28 under no-till and 0.37 to 0.54 under cover cropping. Across the four systems the modelled soil-carbon input ranged from 0.70 to 0.86 and gave a different ordering from the composite.

The scores show how the method's cover-weighted composite distinguished these treatments. The results come from small numbers of plots at one site, in a North American continental ecoregion where the absolute band is uncalibrated.

Estimated cover in four UK comparison cases

Both the Kellogg and the UK comparisons use the same Rothamsted-referenced cover axis. Similar mean bare scores can give different cover-axis values, because the axis combines the annual mean weighted cover with the longest majority-bare run. The Kellogg values describe replicated plots at one site; the UK values describe selected commercial cases.

Table 4 gives median cover-axis scores for four UK cases over matched periods of several years. The four cases draw on four commercial farms and one Morley-area reference block, with the two regenerative farms reported together as one case. The organic continuous-cover farm scored highest, at 0.81, and also provides the provisional upper reference for mapping the four-process composite to the Land Health Score. The no-till business and the conventional reference each scored 0.55 at the reported precision, and the diverse-rotation regenerative case scored 0.51.

The conventional reference is ten field-interior patches of about 3.2 hectares each, digitised from public imagery over one arable block near Morley, Norfolk. They are not registered fields, and their ownership during the assessment years is not established, so the reference anchors a direction of response rather than an absolute. The block lies in the host area of AHDB's Strategic Cereal Farm East, which AHDB has documented as a conventional cereal host farm since 2023, including its rotation (AHDB, 2023); that documented host history is separate from the sampled patches, and the host's nitrogen and cover-crop practices are not established for the patches or for the assessment years. The other commercial farms are described by their management and results; their names, areas, counties

and founding dates are withheld, and field counts and the exact years are held with the confidential boundaries.

The no-till business had carried out its own low-disturbance direct drilling for many years on fields with consent-registered boundaries. Both it and the conventional reference had a mean bare score of about 0.53. The no-till fields recorded about 29 majority-bare weeks a year, compared with about 25 for the reference. Green persistence was slightly lower on the no-till fields. Their weekly normalised difference vegetation index (NDVI) reached 0.30 or higher in about 89 per cent of weeks, against about 92 per cent for the reference.

Why the two cases had the same cover-axis score remains open. Some residue may have registered as bare in the retrieval. Field spectra would help check that possibility. Combinable crops can also leave a gap in living cover between harvest and the establishment of the next crop. Establishing how either case compares with conventional and no-till farms across the UK would require a wider sample.

The farms in the diverse-rotation regenerative comparison used companion crops and reduced synthetic inputs. One also integrated grazing and agroforestry. Across the matched years, their weighted cover and total majority-bare weeks were similar to the conventional reference. Table 4 describes these signals qualitatively against that reference. The farms converted around 2021. Their modelled soil-carbon series end between about 2020 and 2022, close to conversion. The faster cover signal therefore dominates the composite for these cases.

Table 4. Cover-axis scores and underlying signals for the UK cases over matched periods of several years. Scores on the cover axis are case medians of the normalised score, shown to two decimal places. The commercial farms are anonymised. The conventional reference is ten digitised field-interior patches over one block near Morley. Green persistence is the proportion of weeks with a weekly NDVI at or above 0.30. The table counts all majority-bare weeks in a year, while the cover axis uses the longest consecutive run of such weeks.

CASE	COVER AXIS	TOTAL MAJORITY-BARE WEEKS PER YEAR	MEAN BARE SCORE	GREEN PERSISTENCE	ROLE
Conventional reference	0.55	about 25	about 0.53	about 92 per cent	regional reference unit
No-till business	0.55	about 29	about 0.53	about 89 per cent	commercial comparison
Diverse-rotation regenerative	0.51	similar to conventional	similar to conventional	similar to conventional	commercial comparison
Organic continuous-cover	0.81	few	low	high	provisional upper band reference

The lower Rothamsted cover reference pools two experimental fields. The comparisons reflect variation within farms as well as differences among management systems. Kellogg supplies replication across plots within one site, while the proposed multi-farm trial would test how far the ordering holds across UK farms and inform calibration of an absolute UK scale.

The cover axis is calculated from satellite estimates of cover. Management labels describe the systems being compared. In these UK cases, different management labels sometimes accompanied similar cover scores.

Seasonal cover patterns

Figure 8 illustrates four seasonal profiles. Each panel shows weekly medians pooled across the areas assessed for that example and the years 2018 to 2025. Table 4 reports case medians over matched multi-year periods for the specified reference and comparison units. Pooled this way, each system shows a characteristic seasonal signature, a phenological fingerprint in the cover record, clearest in the timing of post-harvest exposure.

The green score stays above zero through winter, consistent with growth in autumn-sown cereals and cover crops. The bare score can also be positive in those weeks. A median across fields and years leaves open how continuously any individual field stayed covered.

The profiles differ most after harvest. In the conventional, no-till and regenerative examples, the bare score rises from its summer low in late summer and early autumn. Fields can be in stubble or cultivated during that interval before the next crop establishes. All three have a higher autumn peak than the organic example, whose bare score is highest in winter.

These are pooled medians that describe a seasonal pattern. Assessing an individual field's exposure and physical cover needs that field's own cover record and field observations. The regenerative panel shows one farm, converted around 2021, and pools years before and after conversion under its current management label. The dotted Hoosfield weekly bare-score trace is shown for comparison and differs from the lower Rothamsted cover reference used for normalisation.

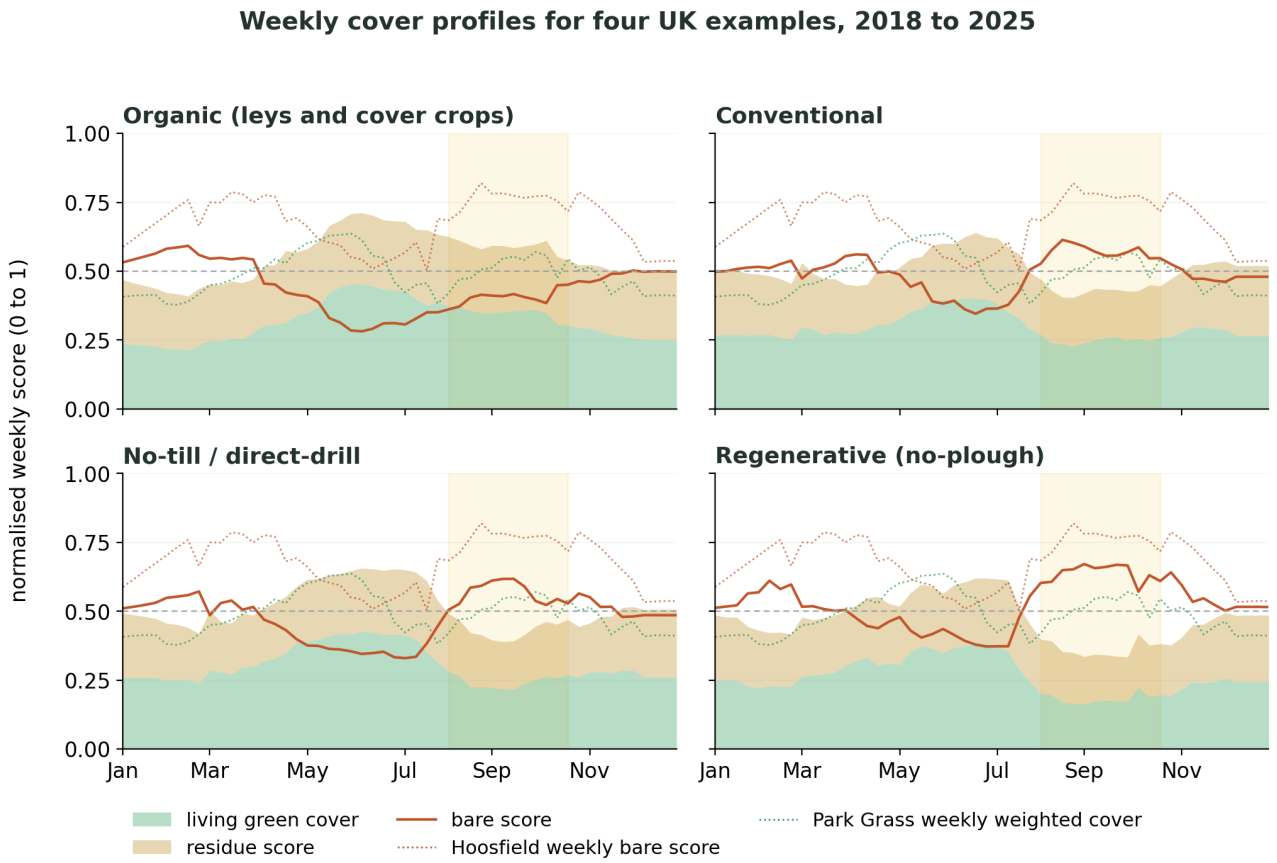


Figure 8. Weekly cover profiles for four UK examples, 2018 to 2025. The organic, conventional, no-till and regenerative examples cover 312, 80, 1,032 and 272 field-years, respectively. The green and tan areas show the living-green and residue scores and the solid orange line the bare score, as pooled weekly medians. The shaded band shows an approximate post-harvest window. The dotted lines show the Hoosfield weekly bare score and the Park Grass weekly weighted cover.

Figure 9 shows where the four Table 4 cases sit between the Rothamsted endpoints. The lower Rothamsted cover reference sets the floor and the Park Grass permanent-grass reference sets the ceiling.

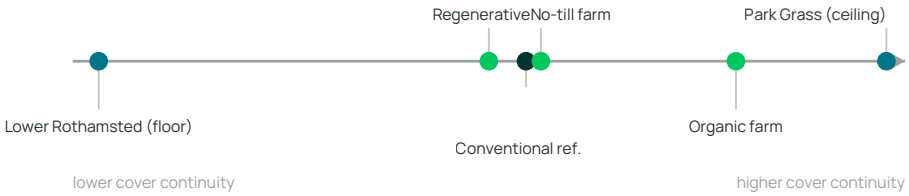


Figure 9. How the UK cases fall along the cover axis. Rothamsted's lower cover reference and Park Grass permanent grass mark the lower and upper ends. The diverse-rotation regenerative case scores 0.51. The conventional reference and the no-till farm both score about 0.55 and are drawn a little apart so both marks are visible. The organic continuous-cover farm scores 0.81, below Park Grass. It provides the upper reference for the provisional Land Health Score bands. The absolute 1 to 9 bands for the commercial farms still require calibration, so the figure shows scores on the cover axis.

An autumn imagery check of field greenness

The finer imagery allows a check of whether the weekly field calls distinguish predominantly green from predominantly non-green ground. The scenes lack shortwave-infrared bands. Both residue and exposed soil can appear non-green.

The study used four archived sub-metre optical scenes representing organic, conventional, no-till and regenerative management, one scene per management case. The scenes were acquired from late August to early October 2021, after the main harvest. Each fell in the same ISO week as its nearest clear Sentinel-2 match. The retrieval called a field majority-bare if its weekly normalised bare score exceeded 0.5. A score of 0.5 or below gave a covered call for this check.

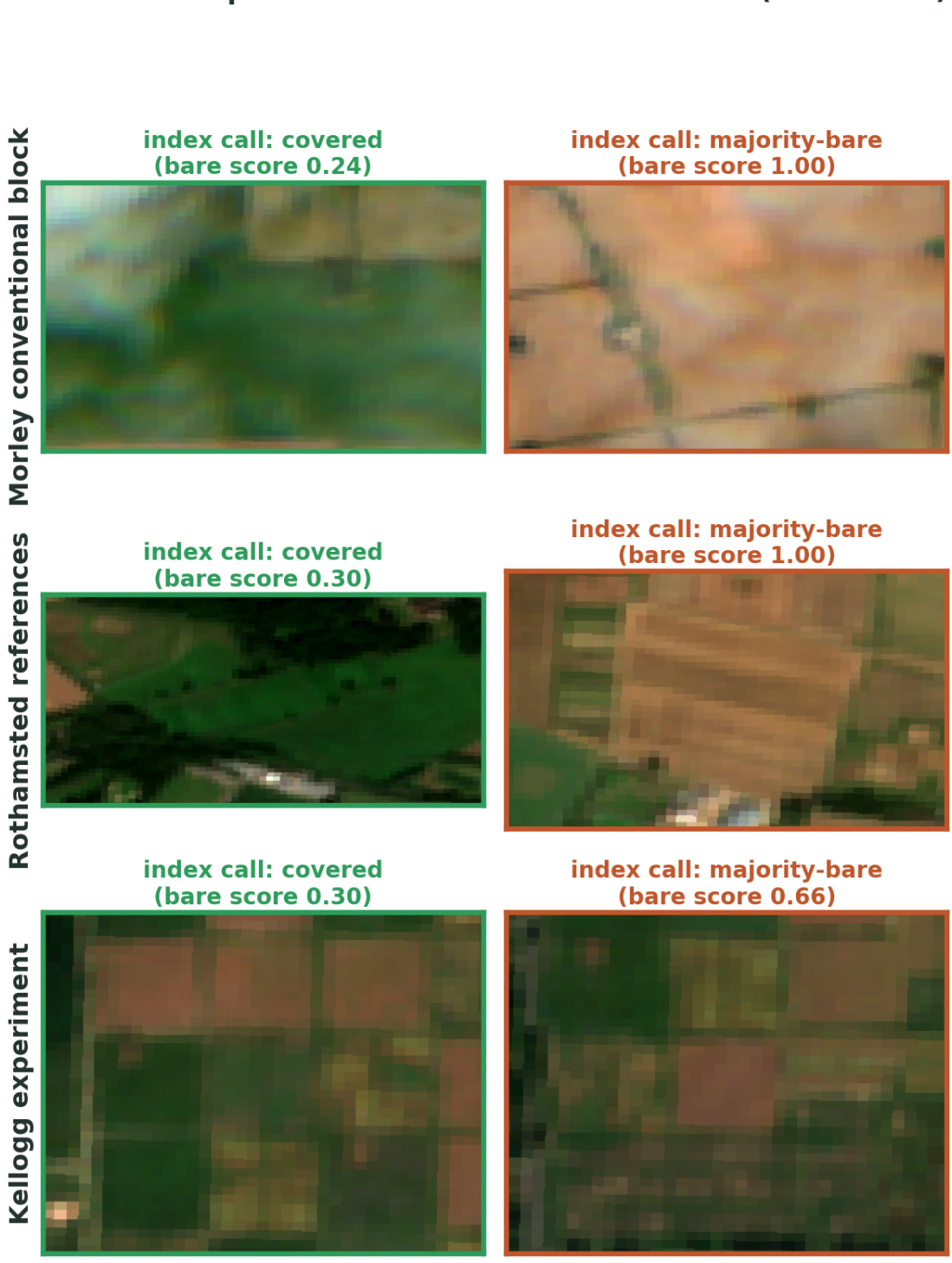
All four scenes carried a near-infrared band. In two scenes, a pixel counted as green if its NDVI exceeded 0.35. Mixed and built pixels counted as non-green. The imagery green fraction for a field was the proportion of pixels that counted as green. A majority-bare call agreed with the imagery if less than half the field's pixels counted as green. A covered call agreed if more than half counted as green. The record leaves open how values of exactly one half were treated. The other two scenes were assessed visually with field boundaries overlaid, because cloud shadow over dark peat and differences in sensor radiometry made the near-infrared index unreliable across sensors.

The author-reported tally covers 43 field samples. The calls agreed with the imagery green fraction on 24 of the 26 fields assessed using NDVI. The visual assessments agreed with the calls on all 17 remaining fields. Both disagreements were on the organic scene. Thin cloud affected one of the two fields, excluding it from the Sentinel-2 composite and leaving a gap-filled value for that week. The other was a stubble field with scattered green volunteers. Thin cloud and scattered green volunteers may explain the two disagreements. Neither case was independently resolved. In the organic scene, the Pearson correlation between the continuous green fractions from the imagery and the green scores from the retrieval was 0.72, a comparison of continuous greenness estimates for that scene.

Table 5. Four autumn 2021 scenes at very high resolution, labelled by management to protect the farms' identities. The conventional scene covers the Morley reference block; its two sampled field interiors are two of the ten reference patches sampled over that block. Each scene falls within its matched Sentinel-2 ISO week and carries a near-infrared band. Two scenes were assessed by index, where a pixel counted as green if the normalised difference of the near-infrared and red bands exceeded 0.35 and the green fraction is the share of a field's pixels that passed; the other two were assessed visually against the field boundaries. The check compared green against non-green ground. Pixel spacing is given as delivered; the sensor's native multispectral resolution is a separate quantity. The images and farm identities stay with the provider.

SCENE (MANAGEMENT)	ACQUISITION	SENSOR AND BANDS	PIXEL SPACING (DELIVERED)	MATCHED S2 WEEK	FIELD SAMPLES	RETRIEVAL BARE / COVERED	ASSESSMENT	AGREE / TOTAL
Organic	26 Aug 2021	WorldView-2, 8 (incl. NIR)	0.54 m	2021 week 34	24	3 / 21	index (pixel NDVI > 0.35)	22 / 24
Conventional	7 Sep 2021	WorldView-2, 8 (incl. NIR)	0.50 m	2021 week 36	2	1 / 1	index (pixel NDVI > 0.35)	2 / 2
No-till	22 Sep 2021	GeoEye-1, 4 (incl. NIR)	0.50 m	2021 week 38	5	4 / 1	visual	5 / 5
Regenerative	6 Oct 2021	GeoEye-1, 4 (incl. NIR)	0.50 m	2021 week 40	12	6 / 6	visual	12 / 12

The Sentinel-2 retrieval classified four of the 26 NDVI-assessed samples as majority-bare. The two disagreements were unrecorded by class, so between two and four of those four calls agreed with the imagery's non-green classification. That class includes cultivated ground, stubble and built surfaces. Each management case contributed one autumn scene, and each single-date image was compared with a weekly composite.



Contains modified Copernicus Sentinel data 2021

Figure 10. Selected Sentinel-2 true-colour examples, for illustration, from the satellite the index uses. Autumn 2021 at public sites: the Morley conventional block (in the AHDB Strategic Cereal Farm East host area), the Rothamsted references (Park Grass and Hoosfield) and the Kellogg experiment. Each row pairs two selected image chips, one the index called covered and one it called majority-bare. The 2021 Morley imagery predates the farm's AHDB host designation in 2023. The separate check in the preceding section tested green against non-green ground on the dates assessed, using licensed sub-metre imagery that cannot be shown here. Contains modified Copernicus Sentinel data 2021.

What the comparisons establish

At Kellogg, every cover-cropped plot had a higher eight-year median composite score than every conventional-tillage plot. The plots were replicated in blocks at one site and shared a climate and regional soil setting. The groups stayed separate under both prairie-strip masks when compared on their 2019 to 2025 plot medians. Cover carries the largest weight in the composite. The proposed trial would vary cover and tillage independently and measure how soil function responds.

Rothamsted supplied the endpoints of the cover axis. The Kellogg result was already known when the retrieval switched from an NDVI-scaled green score to the soil-adjusted index and the Rothamsted endpoints were recalculated, so the rerun cannot serve as a blind test of the chosen retrieval. The margin was 17.4 points in the earlier NDVI-based calculation and 10.6 points after adopting MSAVI2 and recalculating the Rothamsted endpoints. The cover-cropped and conventional plots separated completely in both calculations. Which retrieval better estimates physical ground cover remains open.

The UK results describe how the assessment responded in the selected cases. The comparison with conventional management rests on ten digitised field-interior patches over one block near Morley. These are not registered fields, and their ownership during the assessment years is not established. The provisional UK Land Health Score uses that sample and one organic continuous-cover reference to anchor its scale. A replicated UK comparison of management treatments would give a firmer basis for interpretation. The two-site Rothamsted Large-Scale Rotation Experiment is one candidate. Its suitability would depend on plot geometry, access to the data and the size of the plots in relation to the satellite pixels.

Across field-years in the commercial cohort, the Pearson correlation between productivity and cover was about 0.85. This indicates an association between the productivity and cover indicators in that cohort. The cohort included no high-input intensive farm, so whether the productivity term would raise the score at those input levels remains open.

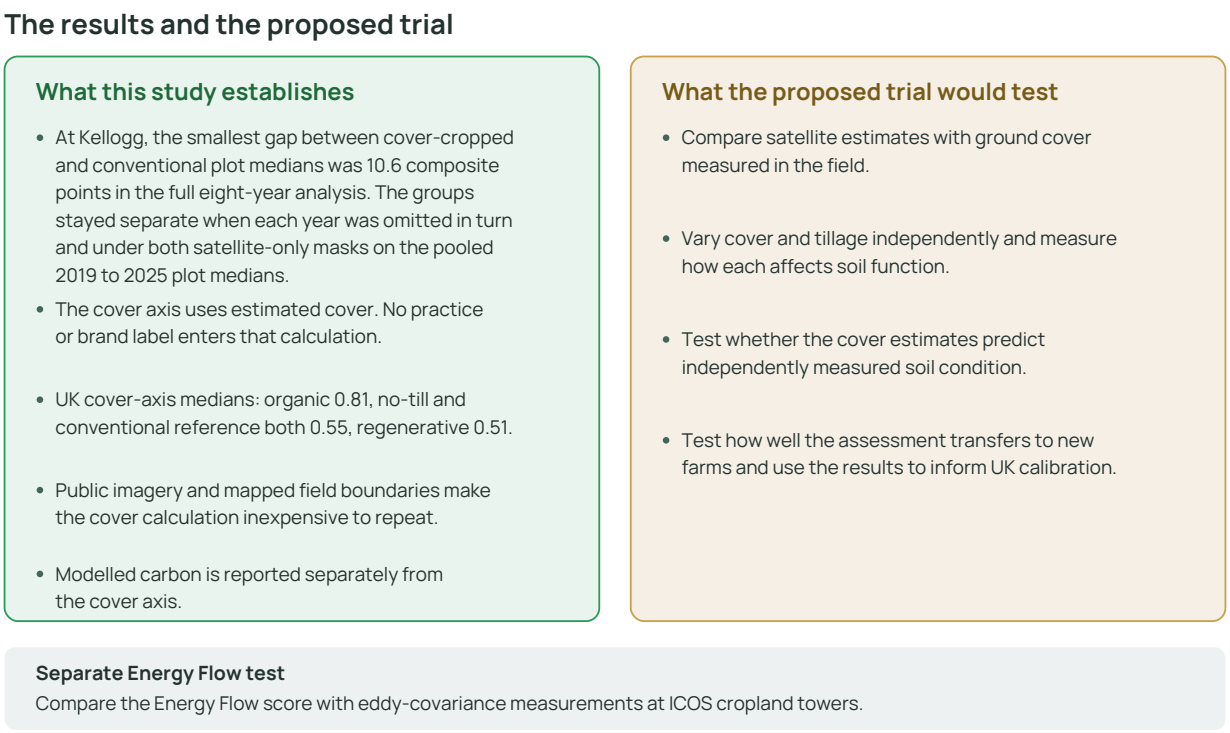


Figure 11. What this study establishes and what the proposed multi-farm trial would test. The UK comparison covers four cases drawn from four commercial farms and one Morley-area reference block. The two regenerative farms are reported together.

What the autumn imagery can corroborate

The autumn imagery check distinguishes green from non-green ground on the dates assessed. Bare soil and standing residue both fall in the non-green class. Sentinel-2's broadband shortwave imagery can help distinguish the two, although wet stubble is particularly hard to separate from bare soil. Sparse, low-biomass growth can also be hard to distinguish from bare ground, especially on recently converted, low-input fields. The residue signal can help distinguish management systems in aggregate. Judging a single field on a single date calls for greater care.

What the soil-carbon evidence tells us

At Kellogg the cover axis distinguished the farming systems more clearly than the modelled soil-carbon input to the Mineral Cycle. The reason the modelled values cluster so closely remains undetermined. Independent soil cores show that the systems differ in soil carbon. In 2001, surface soil carbon was higher under no-till and biologically based management than under conventional management, with the reduced-input system intermediate (Syswerda et al., 2011). In 2013, carbon in the whole profile to one metre was higher under both cover-cropped systems than under conventional management. The no-till mean was numerically intermediate and shared a statistical group with both sides (Cordova et al., 2025). The studies used different depths and sampling bases. Estimating a change in stocks would require comparable measurements over time.

On the recently converted UK farms, the modelled soil-carbon series ends around 2020 to 2022, close to the change in management. What happened to soil carbon afterwards remains unknown. The modelled surface is uncalibrated for absolute soil organic matter on these farms. EDDE models water and energy signals over one to three years, mineral cycling over roughly three to seven years and community dynamics over five to ten years. In the first years after conversion, the seasonal cover record

can give an early indication of changes at the surface. Independent field measurements are needed to establish whether slower soil properties also change.

Optical soil spectroscopy uses light reflected directly from the soil. Combining images of exposed soil over several years can supply enough observations, as Demattê et al. (2020) and Safanelli et al. (2020) describe. In the latter study, tests for topsoil organic carbon concentration gave an R-squared of 0.04 to 0.06 for the satellite composites and 0.24 for laboratory spectra. A field covered for most of the year offers few unobstructed views of its soil. Successive images can still show how its cover changes. Link (2026) describes how EDDE models soil-carbon stocks.

Scope and limitations

Several limitations bound what these results support. The three weekly scores are normalised spectral indices, not measured physical fractions of green cover, residue and bare soil; wet stubble in particular is hard to separate from bare soil, and the autumn imagery check distinguished only green from non-green ground. Optical observation is uneven, so cloud, snow and shadow leave gaps that the method fills to complete the year, and a winter gap can extend an apparent bare run.

The comparisons support bounded inference. The Kellogg result comes from replicated plots at one site in a North American continental ecoregion where the absolute band is uncalibrated, and the UK cases are selected commercial units rather than a representative sample, so neither establishes an absolute UK scale or separates the effects of cover and tillage on soil condition. Hedgerows, margins, field geometry and other habitat structure belong to EDDE's existing whole-farm assessment, not to the field-level cover score; a satellite pixel at the edge of a small field can include adjacent land, and this analysis does not report a reliable association between field geometry and the signal used to look for signs of regeneration.

The current cover score has no variability term. The proposed multi-farm trial is the first step towards Version 2.

How the approach fits with other assessments

The method combines a field-year estimate of exposure with EDDE's four ecosystem processes, an ecoregion reference and a provisional mapping to score bands. Other satellite benchmarks use related Sentinel-2 measures of cover and photosynthesis. Where the estimates agree, the shared source limits how much independent evidence that agreement provides.

The European Alliance for Regenerative Agriculture (2025) uses Sentinel-2 and radar vegetation indices. It uses the variation in NDVI across a field as a proxy for diversity. The Kellogg comparison examines how greenness varies over time. To test how variability in the rotation and field mosaic relates to recovery, the measure of variability would need to be independent of both the composite's cover term and the Alliance's within-field NDVI proxy.

Verra's VT0014 is a digital soil-mapping tool in a carbon-crediting framework (Verra, 2025). It admits both bare and vegetated soils, uses reflectance from bare soil among its predictors and requires physical samples for calibration. Its direct soil spectra come from exposed surfaces.

Using the cover record to design cropping systems

Figure 8 shows when the cover patterns differ during the cropping year. In the conventional, no-till and regenerative examples, the bare score rises in the weeks after harvest. In the organic example it peaks in winter. Each line pools the areas and years assessed for one example. If a similar pattern keeps

appearing on an individual field, the weekly record gives the grower and agronomist a time of year to investigate.

They can start with the harvest and drilling dates. A visit in the weeks when the bare score usually rises can show whether the ground is exposed, protected by stubble or carrying a crop that has only just emerged. The options might include keeping the stubble longer, drilling the next crop sooner or fitting a cover crop into the gap. What fits depends on the crop sequence and the time available for establishment. In a later season, the same assessment can show whether the estimated gap in cover has shortened. Field measurements can then test whether soil function has changed.

Other choices span the rotation. A grass-clover ley, for example, gives the soil longer under living roots than a cover crop between two cash crops. Several years of field records can help a grower and agronomist see where those periods fall and ask whether the rotation gives the soil time to recover. Hedges and margins bring a further set of decisions about the land around the crop. Assessing changes there calls for evidence from those habitats as well as from the cropped surface.

Across a farm, the record can help decide which fields to inspect and when. Across a grain supply area, it can help direct agronomic support and establish a dated record of conditions on the fields assessed. Adding another mapped field or year uses the same imagery archive and calculation, keeping the additional cost low.

Figure 12 shows one field-year as a spectral fingerprint, the seasonal pattern of green, residue and bare scores the method reads to find the exposure period.

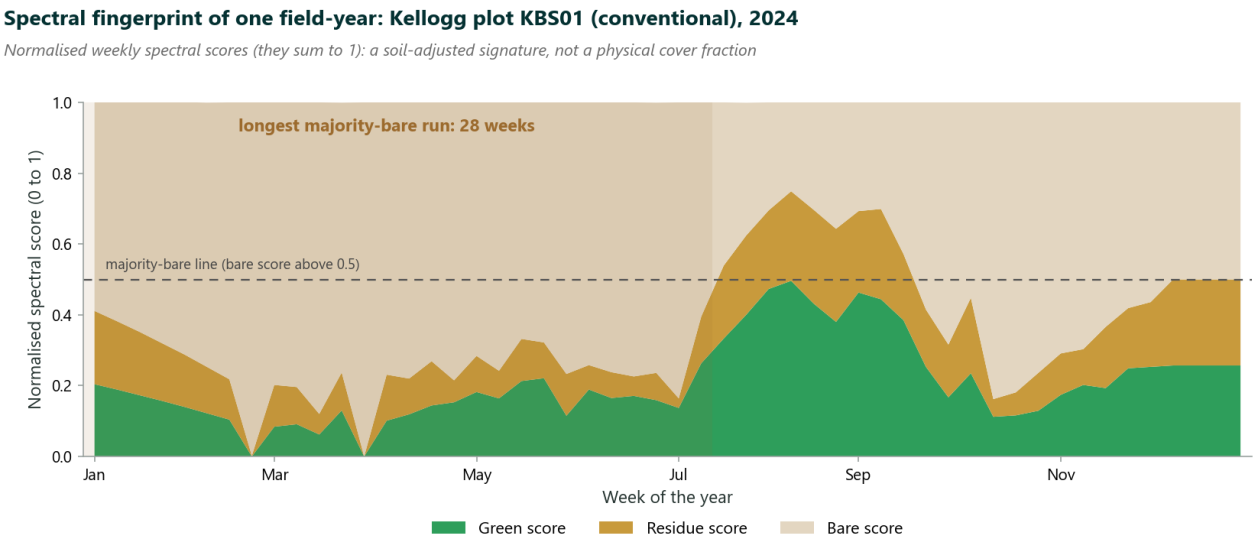


Figure 12. The spectral fingerprint of one field-year: the weekly green, residue and bare spectral scores for Kellogg plot KBS01, a conventional-tillage plot, through 2024. The three scores sum to one in each week. The green score peaks at about 0.5 in summer. A majority-bare week is one in which the bare score exceeds 0.5. This plot had a 28-week run above that threshold. Physical surface fractions require separate observations.

Natural-capital accounting and nature disclosure

Building a cropland condition account

An ecosystem account describes both extent and condition. Mapped fields establish the area assessed. Repeated cover estimates could supply one indicator of its condition. In EDDE, the cover axis feeds the four-process assessment, which is scored against the parcel's ecoregion reference state. An account could record the fields assessed, the dates, the cover estimates and the reference used

in scoring. Using the same method for successive assessments would let the account follow the same fields over time. The cover record describes the hectares assessed. A claim about a product or its derivatives would need independent evidence linking it to those fields.

The UN System of Environmental-Economic Accounting (SEEA) Ecosystem Accounting standard describes condition through composition, structure and function, assessed against a reference level. For cropland that reference can reflect human management, and condition accounts can use individual indicators or composite indices and present area by condition range (United Nations, 2021). A 1 to 9 cropland measure fits as either an indicator or a composite. EDDE applies its ecoregion reference state at parcel scale. In the UK, the Office for National Statistics (ONS) reported in 2022 that it lacked consistent data to calculate a condition index across all habitats (ONS, 2022). Its 2026 enclosed-farmland account reports a wider set of physical, chemical, compositional and structural indicators. It still lacks a single consistent condition measure for cropland (ONS, 2026). Repeatable field-cover estimates could add one indicator to that account.

Using the evidence in sustainability and nature disclosure

An account of the assessed land can supply environmental evidence for a company's sustainability and ESG reporting. On 13 October 2026, the Nature Positive Initiative published a common set of state-of-nature metrics, with aligned updates from the Taskforce on Nature-related Financial Disclosures and the Science Based Targets Network (Nature Positive Initiative, 2026).

Reporting ecosystem area and condition. Within the TNFD LEAP approach (Locate, Evaluate, Assess, Prepare), a cropland condition measure is evidence in the Evaluate phase, which informs the subsequent Assess phase for risks and opportunities. TNFD metric C5.1 calls for reporting ecosystem area and condition by ecosystem type and condition class, as a state and as change over time (TNFD, 2026). The Global Reporting Initiative (GRI) standard GRI 101-7 calls for reporting ecosystem type, size and condition, and the method used to assess it (GRI, 2024). EDDE's reference-based assessment provides condition estimates reported through its Land Health Score bands and underlying indicators; these give evidence of condition and change, reported with the methods and assumptions used, as GRI 101-7 asks. TNFD's global core metrics are a minimum set, and TNFD allows additional, locally relevant metrics where an issue is material; that is the route a cropland condition measure takes. Repeated field-cover estimates contribute to this reporting for arable land in a supply chain.

Selecting metrics for material impacts. For reporting under the EU Corporate Sustainability Reporting Directive (CSRD), ESRS E4 links the metrics an undertaking reports to the biodiversity and ecosystem subtopics material to it. It was revised by Commission Delegated Regulation (EU) 2026/1563, which amended Delegated Regulation (EU) 2023/2772. In selecting metrics, the undertaking considers how often it monitors, what condition or value it starts from and the period that baseline covers. The revision has been in force since 10 November 2026, with a choice of versions for financial years beginning in 2026 and general application from 1 January 2027 (European Commission, 2026). Where an undertaking has material impacts on arable land, repeated cover estimates could inform an indicator for the fields it assesses. A dated record could help it describe condition by ecosystem type and set a baseline for a target.

Establishing a baseline for nature targets. The first steps of the Science Based Targets Network (SBTN) Science-Based Targets for Nature method, updated to Version 2.0 in 2026, assess and prioritise the state of nature across a company's land footprint (SBTN, 2026). Repeated cover estimates could contribute a cropland condition indicator to that baseline across many sites. The company sets its own target and SBTN's Accountability Accelerator provides independent target validation.

Reporting nature risks alongside climate information. For companies using the ISSB standards, a cropland condition indicator could inform reporting on material nature-related risks and opportunities under IFRS S1. The separate carbon layer could inform reporting under IFRS S2 (IFRS Foundation, 2023). The ISSB published its dedicated nature guidance, which draws on the TNFD framework, as an exposure draft (IFRS Sustainability Disclosure Practice Statement 1) on 22 October 2026, with comments open until 19 February 2027 (IFRS Foundation, 2026). EcoIntel supplies evidence and interpretation to support the company's disclosure. The company is responsible for its compliance statement and any assurance it obtains.

Monitoring restoration and market projects. The condition indicator is relevant to Goal A of the Kunming-Montreal Global Biodiversity Framework, which calls for maintaining and enhancing ecosystem integrity, connectivity and resilience. For Target 2, repeated cover estimates could help monitor land already identified as under restoration. The target concerns the area under effective restoration (CBD, 2022). Protected-area extent and progress against area-based targets need separate evidence. A nature-repair or biodiversity-credit scheme operator or verifier could use the estimates to help set a condition baseline and monitor change. Defining the scheme's unit, issuing credits and verifying transactions are separate responsibilities.

Accounting for land-sector carbon. EDDE reports a separate modelled field carbon balance, a distinct use of the data from the condition assessment. The GHG Protocol Land Sector and Removals Standard, which supplements the Corporate and Scope 3 Standards and covers agriculture, takes effect on 1 January 2027 (GHG Protocol, 2026). For project-level quantification, the International Organization for Standardization (ISO) standard ISO 14064-2 sets out how to quantify and report emission reductions and removals (ISO, 2019). The modelled carbon balance supplies one input to that work and to climate disclosure under CSRD ESRS E1, and is reported separately from the cover-based condition indicator.

Supporting deforestation due diligence. The mapped field boundaries and land-use history that EDDE holds can support due diligence under the EU Deforestation Regulation for covered commodities such as soy, where an operator must show that production did not take place on land deforested after the regulation's cut-off date (European Union, 2023). This is a distinct use of the spatial evidence from the condition assessment. The regulation's main application date is 30 December 2026, with a later date of 30 June 2027 for most micro and small operators.

Carbon and cooling alongside cover

EDDE reports the modelled annual field carbon balance and estimates of above-ground biomass alongside the condition assessment. The modelled soil-carbon stock also informs the Mineral Cycle component of the score. Where suitable thermal observations are available, EDDE reports the local difference in land-surface temperature as a separate outcome in degrees.

Looking ahead

Version 1 of EDDE's arable assessment provides reference-based estimates of cropland condition and change over time. It reports them using its Land Health Score bands and underlying indicators. These outputs support natural-capital accounts and nature-related disclosure. Version 2 would use management records and field measurements from a wider range of commercial producers to strengthen UK calibration, test transfer across regions and cropping systems, check the satellite estimates against physical cover, and relate cover to independently measured soil function. The proposed multi-farm trial described below is the first step toward Version 2 and an absolute UK scale.

The proposed multi-farm trial

A grower considering a change to the rotation may want to know which fields lose protection between crops and whether a cover crop would help rain soak in. The weekly record helps decide when and where to look. Field visits can establish what is on the ground, and measurements can show how the soil responds. The proposed trial would bring that evidence together across farms with different soils, climates and rotations.

Does the satellite estimate track physical cover?

The optical test would pair the weekly estimates with field measurements or photographs taken near the time of the satellite overpass. Field observations would distinguish green canopy, sparse emergence, standing and flat dry material, and bare soil. The sample would deliberately include wet stubble. The comparison would report the error in estimates for each surface component, in the classification of majority-bare weeks and in the length of those runs. It would also compare the full composite with the cover component alone and with a simple greenness baseline. Suitable narrowband imagery could provide an additional check on the residue signal.

Does a change in cover or tillage improve soil function?

The study would vary added cover and tillage independently at comparable sites under blocked allocation. Field measurements such as infiltration, aggregate stability or soil-carbon stock would show how the soil responded. The multi-farm design would also allow a test of whether diversity across the rotation and in habitats across the farm predicts recovery. That test would use independent field measurements of habitat structure and a measure of variability independent of the composite's cover term.

How well does the assessment transfer across farms?

Each reference class would need several farms in more than one region. The study would specify in advance how the fields would be described and how the indicators would determine a class. Fields and repeated years would be nested within farms. Whole farms would be held out of calibration, so their field measurements could be used to assess discrimination and calibration error. The held-out farms would include well-covered fields in poor soil condition.

The study would fix the model and success criteria before evaluation. Field assessors would work without knowing the EDDE scores or the intended classes.

Where arable land enters a natural-capital account or nature disclosure, the trial results could refine the condition classes and strengthen their UK calibration.

Help shape the trial

The author invites arable growers and their advisers to bring a question about cover or soil recovery that they want to answer. A grower can help identify a comparison that fits the farm's rotation and share dated records or field photographs. Agronomists and other advisers can help find comparable fields and plan visits around harvest and drilling. Researchers with experience of field trials can help choose measurements and design the comparisons. Grain buyers who know which fields supply them can help bring farms into the study or arrange sampling.

Further testing of energy flow

Open cropland sites in the Integrated Carbon Observation System offer a separate way to test EDDE's Energy Flow score. A comparison with eddy-covariance measurements would specify the flux of interest, the tower footprint, the units and the time window. Gross primary production and net ecosystem exchange are carbon fluxes. A test of energy exchange would use a corresponding measured energy flux.

Conclusion

A practical starting point is to design rotations that bring living roots back sooner after harvest and protect the soil while the next crop establishes.

At Kellogg, the two cover-cropped systems separated from conventional tillage on eight-year plot medians for the four-process composite, and the groups stayed separate under both prairie-strip masks over 2019 to 2025. Among the UK cases, the organic continuous-cover farm scored highest on the cover axis at 0.81, the no-till business and the conventional reference both scored 0.55 at the reported precision, and the diverse-rotation regenerative case scored 0.51. These comparisons give growers and their advisers a reason to look at the cover a system actually maintains.

The arable extension lets growers and advisers compare how cropping systems maintain cover across fields and years. EDDE's existing whole-farm assessment places those outcomes alongside hedgerows, margins, field sizes and landscape position. Version 1 maps the arable composite to the 1 to 9 Land Health Score using provisional UK anchors. Growers and advisers can then choose changes to test, whether for soil recovery, input use or productivity. The satellite method makes that assessment possible across mapped fields and successive years at low marginal cost. A business that can link its purchases to mapped fields can use the same record to track seasonal change and decide where to support growers.

Reported through its Land Health Score bands and underlying indicators, this Version 1 assessment provides a repeatable, reference-based measure of cropland condition and change that can contribute to natural-capital accounts and nature disclosure. The proposed multi-farm trial would test the separate effects of cover and tillage on soil function under the conditions studied.

Appendix A. Exploratory Broadbalk reconstruction

Along Broadbalk's length, sections 0, 1, 6, 8 and 9 are designated continuous winter wheat. Sections 2, 3, 4, 5 and 7 are in rotation, with wheat, oats and beans from 2018 and spring wheat in 2020.

An exploratory satellite-only reconstruction used approximate masks for the continuous-wheat sections, the rotational sections and the full trace. All three gave the same median weighted cover of about 0.28 for the same years. The satellite-only value was higher than the value from the full assessment.

The archive plan is schematic, so the reconstruction used equal bands along the length of the traced footprint. The actual sections vary in length. Rothamsted records section 0 at 15.24 metres and section 1 at 28.04 metres. Section 8, in the continuous-wheat group, was fallow in 2022. The matching medians leave the longest-run endpoint unresolved. Direct recalculation would be needed to find out whether a reference drawn entirely from continuous cereals would give the same weighted-cover and longest-run endpoints. It would also show whether substituting that reference would preserve the Kellogg ranks and margins and the UK ordering.

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Version history

Version 1.2 (2026-11-27). This revision shortens the standfirst and tightens the autumn-imagery and scope-and-limitations passages in response to reviewer comments. The method, data and numerical results are unchanged.

Version 1.1 (2026-11-27). This revision clarifies wording and presentation in response to reviewer comments. The method, data and numerical results are unchanged from Version 1.0 (first published 2026-11-25).

Competing interests

The author, Marcus Link, has a financial interest as founder, CTO, director and shareholder of Ecological Intelligence Ltd (EcoIntel), a limited company registered in England and Wales under company number 16866497 and registered at Brimbles, Ashburton, Newton Abbot, TQ13 7HU. Ecological Intelligence Ltd is the commercial enterprise that employs the EDDE on its platform at ecointel.io. The company is funded by shareholding investors and platform revenue.

Funding

This research was conducted within, and funded by, Ecological Intelligence Ltd, the company that develops the method described. It received no external research grant. The company has raised private investment, as declared under Competing interests.

Acknowledgements

This work uses data from the Kellogg Biological Station Long-Term Ecological Research program, provided under the US Long-Term Ecological Research Network data policy and supported by the National Science Foundation Long-Term Ecological Research Program (DEB 2224712) and Michigan State University AgBioResearch; the published plot geometry used to align the prairie-strip masks is from KBS LTER data table 829 (Environmental Data Initiative, package DOI 10.6073/pasta/12f552a1a21f72e7bc64abdfd684017a). It also uses field management records and site coordinates from the electronic Rothamsted Archive (e-RA), under the e-RA Conditions for Using Datasets and the Creative Commons Attribution 4.0 licence (CC BY 4.0). Contains data supplied by Rothamsted Research. “The Electronic Rothamsted Archive (e-RA), its datasets, information and other resources, are part of the Rothamsted Long-Term Experiments - National Bioscience Research Infrastructure (RLTE-NBRI), funded by the UK Research and Innovation - Biotechnology and Biological Sciences Research Council (UKRI-BBSRC) under award BBS/E/RH/23NB0007 (2023-2028). The RLTE-NBRI is also supported by the Lawes Agricultural Trust.” We thank the Lawes Agricultural Trust and Rothamsted Research for data from the e-RA database. The records used are the Broadbalk, Hoosfield and Park Grass long-term experiment data, including the Broadbalk plan (Rothamsted Research, 2021); the archive is described by Perryman et al. (2018). The Sentinel-2 imagery is from the Copernicus programme.

How to cite: Link, M. (2026). What would it take to make arable farming nature-positive? A satellite and GIS method to assess ecological outcomes, inform the design of arable cropping systems, and support natural-capital accounts and nature-related disclosure (Version 1.2). Zenodo. https://doi.org/10.5281/zenodo.24588634

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