

Effects of ammonia on soil in Scotland with different farming techniques.

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DECLARATION

This dissertation has been composed by me. It has not been accepted in any previous application for a degree, and the work of which it is a record has been done by me. All quotations have been distinguished by quotation marks and sources of information have been acknowledged in the text and cited in the list of references.

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ABSTRACT

Agricultural activities cause release of ammonia into the soil and eventually in atmosphere. However, there could be a difference in amount of ammonia released into the atmosphere depending on the method/type of farming. Release of ammonia further causes acidification of soil due to nitrification process, however if the release of ammonia differs between various methods/type of farming then soil acidification should differ as well. The acidification difference was noticed between organic and conventional farms during field work, however more sampling is recommended to be conclusive as the sample size (number of field work measurements) was small. Although, with decent number of organic farm location data and geospatial analysis of agricultural ammonia, the comparatively lower amount of ammonia was found to be released into the atmosphere.

Additionally, difference in soil composition elements between organic farms and entire agricultural region of Scotland was analysed and found to be negligible which led to a conclusion that organic farms could be maintained similar to any other farm. Also, comparison of soil composition between agricultural and other regions was performed where soil composition was found to be better outside agricultural region. Finally, a multicriteria analysis-based model was also created with AHP method to identify a land class having better soil composition in Scotland.

Keywords: Agriculture, Ammonia, Organic and Conventional farming, Acidification, Soil composition, Geospatial Analysis, Multi-criteria Analysis.

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CHAPTER 1: Introduction

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It is a known fact that agricultural activity causes the release of ammonia (Van Damme et al., 2018). However, this research mainly focusses on identifying the difference of ammonia release into soil/atmosphere due to different types of farming as well as attempts to find better soil composition across Scotland.

To analyse the effects different types of farming has on the soil, a combination of field work and geospatial data analysis techniques were used. Both the techniques were considered necessary as field work provides field specific information and much finer view for comparison whereas geospatial analysis provides coarser view of larger geographical area. The field work involved collecting samples, performing measurements and gathering qualitative information about farming practices while geospatial data analysis involved gathering quantitative data about soil composition, pesticides, atmospheric ammonia, land cover classification across Scotland and using ArcGIS Pro and ArcPy to analyse, visualise maps and drawing conclusion from the data considering geolocation of the farms.

Largely, the fieldwork activities were focussed in Aberdeenshire region of Scotland, from where the soil samples were collected, pH levels were measured on site and questions were asked to farmers about farming practices. In total, three farms were physically visited and three additional farm owners were contacted for surveys. Although, it was known from the beginning that limited data and measurements could be gathered about organic farms with field work, hence details of the organic farms around Scotland were gathered from Soil Association as well. Further, locations of the organic farms were overlaid with ammonia emissions and

other geospatial datasets to analyse the differences in data between organic farms and rest of the agricultural region.

Geospatial datasets (Rasters and Feature classes) were acquired from Edina Digimap, United Kingdom Soil Observatory, National Atmospheric Emissions Inventory, UK Centre of Ecology & Hydrology, Spatialdata.gov.scot, Scotland's Soil, and other sources. The coordinate systems of the datasets were projected to British National Grid for ensuring different datasets are geographical aligned before analysis. Further, all the datasets were reviewed for associated attributes, transformed for better visualisation using geospatial toolsets available in ArcGIS Pro and valuable conclusions were drawn with respect to the locations of the organic farms across Scotland.

Further, the UKSO dataset having soil composition data such as Carbon Concentration, Loss-on-ignition, Carbon Density, Carbon Nitrogen Ratio, Nitrogen Concentration, Olsen Phosphorus, Bulk Density and pH levels were processed through a model created using multi-criteria analysis technique. The model used Analytical Hierarchy Process (AHP) method to determine which soils around Scotland is found to be better in composition. The model involved defining a goal, available alternatives, criteria and detailed process for applying weights, scoring and ranking to determine the model outcome. Finally, the model outcome was reviewed to identify land class with better soil composition.

CHAPTER 2: Literature Review

CHAPTER 2: Literature Review

Excess release of ammonia (NH_3) from agricultural and industrial activities has an impact on the surrounding environment causing acidification of ecosystems (Van Damme et al., 2018). The largest amount of ammonia release results from agriculture and animal farming. Further, a need to satisfy food demand will cause more agricultural emissions of NH_3 (Behera et al., 2013). Use of nitrogen (N) based fertilisers can cause nitrate contamination of water resources and increased emissions of ammonia (Spiertz, 2010). Higher yield of crop is achieved through higher use of agricultural products such as fertilisers and pesticides (Spiertz, 2010). On the other hand, besides agricultural practices for higher yields with conventional methods, the sustainable agriculture produces good crop output with minimal impact on environment considering soil fertility (Mader et al., 2002).

When ammonia gets released in the soil, a microbial process oxidises ammonia into nitrite and nitrate (Nitrification, 2002). Further, release of nitrite and nitrate levels in the atmosphere reduces alkalinity, pH, dissolved oxygen, and chloramine residuals in water (Nitrification, 2002). Also, the pH levels, texture, temperature and moisture of soil is determined by the amount of ammonia volatilisation (Al-Kanani et al., 1991).

Eventually, ammonia gets released from soil into the atmosphere with the process known as Ammonia volatilisation (Killpack et al., 2022). Ammonia volatilisation risk is even higher with the use of fertilisers such as ammonium bicarbonate, urea, and ammonium hydroxide fertilisers, while ammonia loss is

lower with the use of ammonium sulphate or diammonium phosphate fertilisers (Cameron et al., 2013). On the contrary, ammonia losses from urea were lower if injected 2.5cm below the land surface, whereas ammonia losses were higher when the urea was placed 7.5cm below the ground (L. B. Fenn and S. Miyamoto, 1981).

Due to the known effects of ammonia, soil composition elements are also essential for analysis. The amount of organic matter in soil determines soil quality (Robertson S., 2011, Pimentel et al., 2014), amount of dry soil defines degree of soil compactness (Trace & Save, 2023), C:N ratio determines nitrogen availability (Gerald, 2019), effects of Olsen-Phosphorus on soil (Qihua et al., 2020), total nitrogen range which increases crop yield and affects soil health (Compost Interpretation, 2023, Hossen et al., 2021) and need for health pH levels in the range between 5.5 and 8.0 (Rust et al., 2000). Further, different fertilisers also have different effects on pH levels (Zhang et al., 2020, Wang et al., 2023, Balasubramani et al., 2017, Tkaczyk et al., 2020) and different pH could be suitable for different crops (Agricultural Lime Association, 2023). Additionally, types of macronutrients such as carbon, nitrogen, and phosphorus which gets absorbed by the plants can affect the soil (Morgan et al., 2013). Thus, non-agricultural land could also be found better in amount of organic matter and carbon (Shultz, 2018) compared to agricultural land.

For the purpose of this research, agricultural ammonia emissions from National Atmospheric Emissions Inventory were studied. Further, usage of fertilisers and pesticides was also reviewed. The data is collected by British Survey of Fertiliser Practice and Pesticides Usage Survey (UK Centre for Ecology & Hydrology, 2021) were analysed as well. Furthermore, variety of soil data available from UK Soil Observatory (UKSO, 2023), along with Land Cover Map (Crop) from

UKCEH provided by Edina Digimap, and Land Capability of Agriculture from James Hutton Institute and made available through Scottish Government website ([Spatialdata.gov.scot](https://spatialdata.gov.scot), 2020) were also collected and reviewed. Additionally, data about organic farms were received for additional analysis from Soil Association (Soil Association, 2023).

Finally, usage of multi-criteria analysis-based modelling technique was considered preferable over traditional problem-solving approaches (Carver, 1991), and different methods of multi-criteria analysis were referenced before choosing Analytical Hierarchy Process for modelling (Dean, 2022).

CHAPTER 3: Methodology

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3.1. The Quest

As the agricultural activities are found to be linked with ammonia release and subsequent nitrification process. It is essential to ask a question whether there could be a difference in release of ammonia between organic and conventional farming? Moreover, could there be any difference in soil acidification for different types of farms such as arable, pastoral or mixed farms? Also, question arises that which part of Scotland has better soil considering essential soil nutrients? These questions had surfaced while analysing gaps when many literatures were reviewed to understand connection between ammonia and soil health. So, to find answers for these questions, a research with organic and conventional farms around Scotland was considered necessary. Although, visit to large number of organic and conventional farms was not possible given the time frame, hence a unique method was derived where field work and geospatial analysis were planned to be conducted in parallel. Details about the both are as follows.

3.2. Method

A method with following two processes were identified for performing the research.

1. Fieldwork to collect measurements and qualitative information, and geospatial analysis to be performed separately. Later combined data to be processed through geo-processing tools for transformation and analysis to study patterns.
2. A model was created using Multi-criteria Analysis to identify better soil considering soil composition and land classes across Scotland.

3.3. Process 1 & Process 2

Initially as part of process 1, the field work activities were expected to occur intermittently over a period of a month in parallel with geospatial analysis as there was no direct dependency between the two. Later, both geospatial data and field work data were combined for analysis. Once process 1 completed, all the data were brought together for modelling process.

3.3.1. Process 1: Geospatial Analysis & Field Work

3.3.1.1. Field Work

- 1) Acquired required device and followed up with Scotland's Rural College (SRUC) to plan a field visit.
- 2) Visited SRUC on planned date to acquire measurements.
- 3) Visited other farms for data collection.

3.3.1.2. Spatial datasets extraction and ArcGIS Pro import

3.3.1.3. Geographical Coordinate System confirmation for each dataset and projection

3.3.1.4. Geospatial representation of Field Work/Soil Association Data

3.3.1.5. Dataset Analysis, Attribute tables review, Geoprocessing and Pesticides processing (ArcPy)

3.3.1.6. Maps visualisation, overlay, comparison and result analysis to draw meaningful conclusions

3.3.2. Process 2: Modelling

3.3.2.1. Identify land classes for modelling (Land Cover Map)

3.3.2.2. Apply Multi-criteria Analysis to process the land classes and soil composition attributes. Use Analytical Hierarchy Process for modelling.

3.3.2.3. Definition of Goals, Criteria, and Alternatives for the model

3.3.2.4. Prioritisation, Scoring and Ranking of alternatives in the model

3.3.2.5. Identify preferred alternative

3.3.2.6. Discuss the model outcome

3.3.1. Geospatial Analysis & Field Work

3.3.1.1. Field Work

Field work was performed physically at three locations and farmers of additional three locations were contacted over the phone for survey inputs as physical access to their farms could not be ensured. During the field work, samples were collected for measuring pH levels with the use of pH meter (refer [Appendix I](#) for measurement method used) and questions such as personally identifiable information, method of farming (Conventional/Organic), type of farm (Arable, Pastoral or Mixed), end product, name of the fertiliser product used, name of the pesticide product used, and type of soil (Sandy, Silty, Peaty, Clay etc.) were asked along with geolocation of the farm was also captured. The survey responses were captured either using survey123 from ArcGIS, email or over the phone depending on how the farmers were comfortable responding (refer [Appendix II](#) for further details on gathering survey).

First, an organic farm managed by SRUC in Aberdeenshire was visited on 13th June 2023 which had an arable farm as well as grazing farm for animals. Similarly, another organic farm was visited on 16th June 2023 at New Aberdour in Aberdeenshire which had three separate fields: an arable field for growing cereal,

grazing field for animals, and a silage field for hay. For comparison, a conventional farm managed by SRUC in Aberdeenshire was also visited on 26th June 2023 where arable, grazing and silage fields were maintained separately.

3.3.1.2. Geospatial Datasets in ArcGIS Pro

Although field work provides specific farm level data and measurements, whereas geospatial datasets provides broader view of the data across Scotland and beyond. Due to limited on number of farms which could be visited during the research period, it was considered necessary to perform supplemental analysis using geospatial data as described below.

I. Geospatial Datasets

For geospatial analysis, fertilisers and pesticides data was received from UK Centre for Ecology and Hydrology (UKCEH). Agricultural data from EDINA Digimap, essential data such as carbon, nutrients, pH and bulk density were accessed from United Kingdom Soil Observatory. Atmospheric Ammonia data for agricultural activities was retrieved from National Atmospheric Emissions Inventory. Soil Parent Material data was available from British Geological Survey. Land Capability for Agriculture data from James Hutton Institute was made available via Spatialdata.gov.scot. Further, organic farm locations was received from Soil Association for the analysis.

II. Land Cover Map: Crop data (available at EDINA Digimap)

Land Cover Map (Crop Data) is a geodatabase feature class provided by UKCEH and it is downloadable from EDINA Digimap. The dataset has attribute table populated with crop names across Scotland. The dataset is projected in British National Grid coordinate system.

III. United Kingdom Soil Observatory (UKSO) Datasets

The UKSO datasets references British National Grid as a geographic coordinate system and data is made available in the form of shape files with attribute tables. Along with carbon, nutrients, pH and bulk density, additional data such as Land Cover Map class, Land Cover Map number, Dominant Grain, CaCo₃ Rank are made available in the attribute tables.

A. Carbon Data

UKSO has collected Loss-on-ignition (%), carbon concentration (g/kg) and carbon density (t/ha) from 0-15 cm soil depth of topsoil (Henry et al., 2012a). In total, 2614 cores were analysed from 591, 1km x 1km squares around Great Britain (Henry et al., 2012a). Further details about process of measurements is provided by United Kingdom Centre for Ecology & Hydrology at <https://catalogue.ceh.ac.uk/documents/9e4451f8-23d3-40dc-9302-73e30ad3dd76>.

B. pH and Bulk Density Data

UKSO has measurements for pH levels and Bulk Density at 0-15cm soil depth (Henry et al., 2012b). A total of 2614 cores from 591 1km x 1km squares across Great Britain were collected (Henry et al., 2012b). Further, details about process of measurement for pH and Bulk Density is provided by UK Centre for Ecology & Hydrology at <https://catalogue.ceh.ac.uk/documents/5dd624a9-55c9-4cc0-b366-d335991073c7>.

C. Nutrients Data

UKSO provides data for total nitrogen concentration (N) in percentage, Carbon-to-Nitrogen ratio and Olsen-Phosphorus (mg/kg) collected at 0-15cm soil

depth (Henry et al., 2012c). Analysis of 256 1km x 1km squares of cores across Great Britain was performed. For total nitrogen concentration and Carbon:Nitrogen ratio, a total of 1024 cores were analysed, and for Olsen-P, a total of 1054 cores were analysed (Henry et al., 2012c). Further, details about process of measurement for Total Nitrogen concentration, C:N Ratio, and Olsen-Phosphorus is made available by UK Centre for Ecology & Hydrology at <https://catalogue.ceh.ac.uk/documents/7055965b-7fe5-442b-902d-63193cbe001c>.

IV. National Atmospheric Emissions Inventory Dataset

Atmospheric Ammonia concentration data is made available by National Atmospheric Emissions Inventory. The organisation has segregated ammonia emissions by sectors including agricultural sector. The ammonia emissions are measured in tonnes/km². The data is originally sourced from Ordnance Survey, Royal Mail, and National Statistics. The dataset has British National Grid as a reference coordinate system and files are available as rasters in ASC format. Further details about the dataset is available at https://naei.beis.gov.uk/data/map-uk-das?pollutant_id=21

V. Land Capability for Agriculture data from James Hutton Institute

Land capability for Agriculture dataset is made available by James Hutton Institute at Spatialdata.gov.scot website. The dataset defines seven classes of land capability classification for agriculture in Scotland. The land is ranked based on agricultural productivity and crop flexibility of the land. Class 1 identifies land to be capable of producing wide range of crops whereas class 7 is identified as land capable of limited agricultural use. British National Grid is the projected coordinate

system of the dataset with scale factor of 1:250,000. The dataset is available in shape file format.

VI. Organic farms from Soil Association

As only limited number of farmers could have been contacted for field work, SRUC provided reference to contact Soil Association for additional organic farmers' locations. Soil Association is an organic certification body which assists farmers with organic certification and farm transformation. Total of 29 organic farms could be located and confirmed using Google/Google Maps based on the name and license number information received from Soil Association (Soil Association, 2023). The data was converted to shape file and projected to British National Grid reference coordinate system.

VII. Pesticide data from United Kingdom Centre for Ecology and Hydrology (UKCEH) (available at EDINA Digimap)

UKCEH has Land Cover plus pesticides data for entire United Kingdom at 1km resolution. It is the created by combining Land Cover Crops datasets and Pesticide Utilisation Survey (PUS) dataset for 162 active pesticide ingredients while also considering uncertainty of application. The measurements of pesticide applications are in kg/km² units annually. The dataset has GCS OSGB 1936 (British National Grid) as a reference coordinate system and files are available as rasters in TIFF format.

3.3.1.2.1. Data Import

Above described datasets were downloaded from their respective website in compressed zip file format. The compressed datasets were then extracted using

windows zip utility before importing them into ArcGIS Pro using Catalog panel after adding a folder connection to the folder location of the datasets.

3.3.1.3. Coordinate System Projection

All the useful datasets mentioned earlier were verified to be having same coordinate system to ensure further analysis is relevant to the geographical area being studied. All the datasets were confirmed to have projected coordinate system to be British National Grid (GCS OSGB 1936).

3.3.1.4. Geospatial representation of Fieldwork Data

Precise location coordinates were gathered using Google Maps during fieldwork at all the farms including individual fields. As Google Maps uses GCS WGS 1984 coordinate system (Google Maps Platform, 2023), latitude and longitude coordinates of each locations were captured. Along with location coordinates, other information about farm such as type of farm and method of farming from survey conducted was saved into a CSV file. The file was then converted to shape file with British National Grid coordinate system projection using Convert Coordinate Notation tool from ArcGIS Toolbox (Refer [Appendix III](#) for the details about the use of Convert Coordinate Notation tool).

3.3.1.5. Geospatial representation of Soil Association Data

Soil Association had provided name, license numbers and farm production details of the organic farmers registered with them. Additionally, their geographic locations were confirmed using Google Maps for geospatial use. Subsequently, the latitude and longitude coordinates of all organic farms were captured and saved into CSV file along with other data received from Soil Association. Further, using the Convert Coordinate Notation tool, the CSV file was converted to shape file with

British National Grid as projected coordinate system (Refer [Appendix III](#) for the details about the use of Convert Coordinate Notation tool).

3.3.1.6. Dataset Analysis, Attribute tables review, Geoprocessing and Pesticides processing (ArcPy)

I. Agricultural Region Analysis

Initial analysis of agricultural region across Scotland was performed with Land Capability for Agriculture dataset. As per the attribute table, there are 7 different classes of land defined across Scotland. Hence, it was essential to further visualise and compare most productive region of Scotland (class 1) with the least productive region (class 7) across Scotland. However, to analyse visually, the dataset was first required to be converted from shape file to raster using Feature to Raster tool from ArcGIS toolbox (Refer [Appendix IV](#) about how Feature to Raster tool was used). This not only offered visual comparison between classes, but also analysis of classes with respect to the location of fieldwork farms and Soil Association organic farms around Scotland.

II. Land Cover Map: Crop Data

The attribute table of this geodatabase feature class has range of crops listed by geolocation across agricultural region of Scotland. To appropriately visualise the crop data, the geodatabase file is required to be converted to raster based on the crop_name field. Hence, Feature To Raster tool of ArcGIS Pro was used for the conversion process (refer [Appendix IV](#) for details about the usage of Feature To Raster tool). Further, Symbology was used to colour code the crops for differentiation on the map (refer [Appendix V](#) for usage of Symbology tool).

III. Agricultural Ammonia Emissions Analysis

Agricultural Ammonia dataset available from National Atmospheric Emissions Inventory is a raster file in ASC format. For visualisation of the raster, Symbology tool of ArcGIS was used to colour code and classify the range of values in 20 different classes for comparative analysis with Land Capability raster from the previous section (Refer [Appendix V](#) for details about using of symbology in ArcGIS Pro).

IV. Agricultural Ammonia and Organic Farms

To further analyse the difference between ammonia emissions around organic farms (Soil Association) and rest of the agricultural region in Scotland, additional calculations were required to be performed using Map Algebra. Before using Map Algebra, organic farm shape file was needed to convert into a raster using Feature to Raster tool of ArcGIS Pro (Refer [Appendix IV](#) for details about Feature to Raster tool). After the raster conversion, Map Algebra tool from ArcGIS toolbox was used to apply calculations between Agricultural Ammonia raster and Organic Farms raster (refer [Appendix VI](#) for details about running map algebra calculations).

V. Soil Analysis of UKSO Datasets

Reviewing the attribute table of UKSO datasets, it was found to have essential soil composition data such as Carbon Concentration, Loss-on-ignition, Nitrogen Concentration, C:N ratio, Olsen-Phosphorus, pH and Bulk Density.

A. Loss-on-ignition (LOI)

Loss-on-ignition (LOI) is a method used to calculate percentage of organic matter (Robertson S., 2011). The 10g dry soil sample was ignited at 375°C for 16 hours (Henry et al., 2012a). Calculation of LOI is simple percentage difference of weight of the sample before the process and after the process (Robertson S., 2011).

The percentage conveys the amount of organic matter the sample had (Robertson S., 2011). So, if the percentage is higher, the soil is considered richer in organic matter.

B. Carbon Concentration

Carbon Concentration indicates the quality of soil, it refers to the amount of organic matter in the soil (Pimentel et al., 2014). It was measured by UKSO in grams per kg and calculated by multiplying 0.55 with LOI (Henry et al., 2012a). If the organic matter content is determined to be higher, then the soil is considered better for plants and agriculture (Pimentel et al., 2014).

C. Bulk Density

Bulk Density (measured in g/cm^3) refers to the amount of dry soil present; it indicates degree to which the soil is compacted (Trace & Save, 2023). Soil with high bulk density cannot provide required nutrients to the plants (Trace & Save, 2023). So, if the bulk density is lower, the soil fertility is considered better.

D. Nitrogen concentration

Nitrogen concentration is measured in percentage, and normal range for total nitrogen is 0.5 to 2.5 (Compost Interpretation, 2023). Nitrogen is an important nutrient as it directly affects crop health, and it can increase crop yield when supplemented in required quantity and timing (Hossen et al., 2021).

E. C:N Ratio

C:N Ratio is Carbon-to-nitrogen ratio. It is the ratio of organic matter which determines amount of carbon present relative to the amount of nitrogen (Gerald, 2019). C:N ratio 20 means there is 20g of carbon for each gram of nitrogen in the

organic matter (Gerald, 2019). C:N ratio of 1-15 results in rapid mineralisation and nitrogen is available for plant use, whereas ratio between 20 and 30 is equilibrium state between mineralisation and immobilisation, and ratio more than 35 results in microbial immobilisation (Gerald, 2019).

F. Olsen-Phosphorus

Olsen-Phosphorus (measured in mg/kg) has major effect on soil crop yield (Qihua et al., 2020). To achieve high Phosphorus Use Efficiency (PUE), crop yield and soil fertility, the Olsen Phosphorus needs to be between 10 to 40 mg/kg (Qihua et al., 2020).

G. pH levels

pH level is a general indicator of soil fertility. The optimum pH range is generally between 5.5 and 8.0 (Rust et al., 2000). Soil pH below 5.5 are acid and inappropriate for agriculture (Leon et al., 2004).

To analyse, visualise, and compare the above-mentioned soil composition attributes, the available shape files must be converted to rasters referring to one of the soil properties. To achieve this, Feature To Raster tool of ArcGIS Pro was used for the conversion (refer [Appendix IV](#) for additional details about raster conversion). The same process was repeated for all the mentioned soil composition attributes.

VI. UKSO Datasets and Organic Farms

Combined analysis of UKSO datasets and organic farms (Soil Association) was not straight forward, as soil attributes needed to be analysed exactly at specific geolocation where organic farms were located. For this reason, geospatial join was

required to be performed between the organic farms shape file and UKSO datasets shape files (carbon, nutrients, pH and bulk density). This resulted in carbon, nutrients, pH and bulk density data getting specifically linked to the organic farm locations. To perform the join, Spatial Join tool of ArcGIS Pro was used which performs join between feature classes based on the geospatial locations (Refer [Appendix VII](#) for use of Spatial Join tool). Further, statistics for each soil attribute (LOI, Carbon Concentration, Nitrogen Concentration, Olsen Phosphorus, C:N Ratio, pH and Bulk Density) for organic farms were also collected using statistics option.

On the other hand, Land Cover Map (Crops) dataset shape file which has crops data across UK (refer fig. 2) was spatially joined with Scotland boundary shape file to only retain agricultural data of Scotland only (Refer [Appendix VII](#) for use of Spatial Join tool). Further, the retained agricultural data of Scotland was spatially joined with UKSO carbon, nutrient, pH and bulk density shape files which resulted in retaining soil attributes of agricultural region within Scotland only (Refer [Appendix VII](#) for use of Spatial Join tool). Subsequently, statistics were collected for the soil attributes for agricultural region to be compared with the statistics collected earlier for organic farms.

VII. Heavily Used Pesticides (ArcPy)

162 different pesticide ingredients were available in UK Centre of Ecology & Hydrology dataset and more than one pesticide (kg/km^2) have been found to be applied across many locations around Scotland. Thus, identifying the locations where pesticides were being applied in high quantity was considered useful. First, to determine the locations, first script was written using Python/ArcPy which

processed thru 162 different pesticide rasters, exporting locations (Easting & Northing), pesticide name and quantity into individual CSV files. Next, only the location data was gathered from 162 different individual CSV files using one more script. With another script, all the CSV files were merged together to create single CSV file with all pesticides data. Subsequently, the single CSV file was processed with another script to sort the pesticides per location and filter out heavily used pesticides for each location across Scotland into a final CSV file (refer [Appendix VIII](#) for details about Python/ArcPy scripts). Eventually, the UKSO Carbon dataset was joined with the final CSV using XY Table To Point tool of ArcGIS Pro to convert CSV to shape file (refer [Appendix IX](#) for details about XY Table To Point tool). The shape file was converted to raster for visualisation using Feature To Raster tool of ArcGIS Pro (refer [Appendix IV](#) for additional details about raster conversion).

3.3.1.7. Maps visualisation, overlay, comparison and result analysis

Refer '[Results & Discussion](#)' section for map visualisation, comparison and results analysis.

3.3.2: Modelling

3.3.2.1. Land Cover Map Classes (UKSO dataset)

Before proceeding with modelling, all the required data was analysed in the available dataset. Land Cover Map Class (LCM Class) was a common attribute identified in all the UKSO datasets. The field identifies each 1 square kilometre land with one of the habitat classes such as Bog, Arable and Horticulture, Coniferous Woodland, Broadleaved Woodland, Improved Grassland, Rough Grassland, Heather Grassland, Acid Grassland, Heather, Neutral Grassland, Fen, Marsh and Swampland. To visualise which area across Scotland is identified with different sets of land classes, Feature To Raster tool of ArcGIS Pro was used to create raster from one of the UKSO shape files using the LCM Class field (refer [Appendix IV](#) for additional details about raster conversion).

3.3.2.2. Multicriteria Analysis based Model using Analytical Hierarchy

Process

I. An overview of Multi-criteria Analysis (MCA)

Due to the shortcomings of traditional decision-making techniques, a multidimensional decision and evaluation model is considered which provide tools for analysis with complex trade-off between alternatives (Carver, 1991). The basic purpose of MCA technique is to analyse multiple criteria, and generate a compromise by ranking the alternatives (Carver, 1991 citing Janssen and Rietveld, 1990). There are various methods for implementing multi-criteria analysis, mainly classified into formal and simplified methods (Dean, 2022). Formal methods have detailed procedures, rigorous rules, and mathematical principles (Dean, 2022). On the other hand, simplified methods are basic and used for rough MCA applications (Dean, 2022). Formal methods are further classified into continuous methods and

discrete methods (Dean, 2022). Continuous method typically deals with problems of infinite nature, whereas discrete methods works with alternatives which are limited in numbers (Dean, 2022).

II. Brief about Analytical Hierarchy Process (AHP)

There are several discrete methods, one of them is Analytical Hierarchy Process method (Dean, 2022). This method attempts to reduce a decision problem into series of smaller self-contained ones as human mind is unable to consider too many factors for making decision (Dean, 2022). It arranges elements in three levels such as Goal, Criteria and Alternatives (Dean, 2022). Given the nature of the problem in this research where problem is of discrete as soil properties and soil classes are known to be limited in number, hence Analytical Hierarchy Process method is chosen to be a suitable method for modelling.

III. Data selection for AHP

As the purpose of creating a model was to find best suitable soil around Scotland, therefore a dataset rich in soil characteristics was needed to be used. Considering a model for better soil, UKSO dataset was selected for the use of AHP method as it had wide range of soil composition attributes. Specifically, Loss-on-ignition, CN Ratio, Carbon Concentration, Nitrogen Concentration, Olsen Phosphorus, Bulk Density and pH levels along with LCM (Land Cover Map) Class attributes were identified to be useful for the model. The reason to choose for the mentioned soil attributes as they are essential indicators of soil fertility (refer '[Soil Analysis of UKSO Datasets](#)' section for details).

3.3.2.3. Definition of Goals, Criteria, and Alternatives

As described earlier, AHP method focusses on defining three levels, namely Goal, Criteria, and Options (Alternatives) as shown in fig. 1. Considering the decision problem about identifying better soil class, following elements of analysis were defined.

I. Decision Problem/Framework

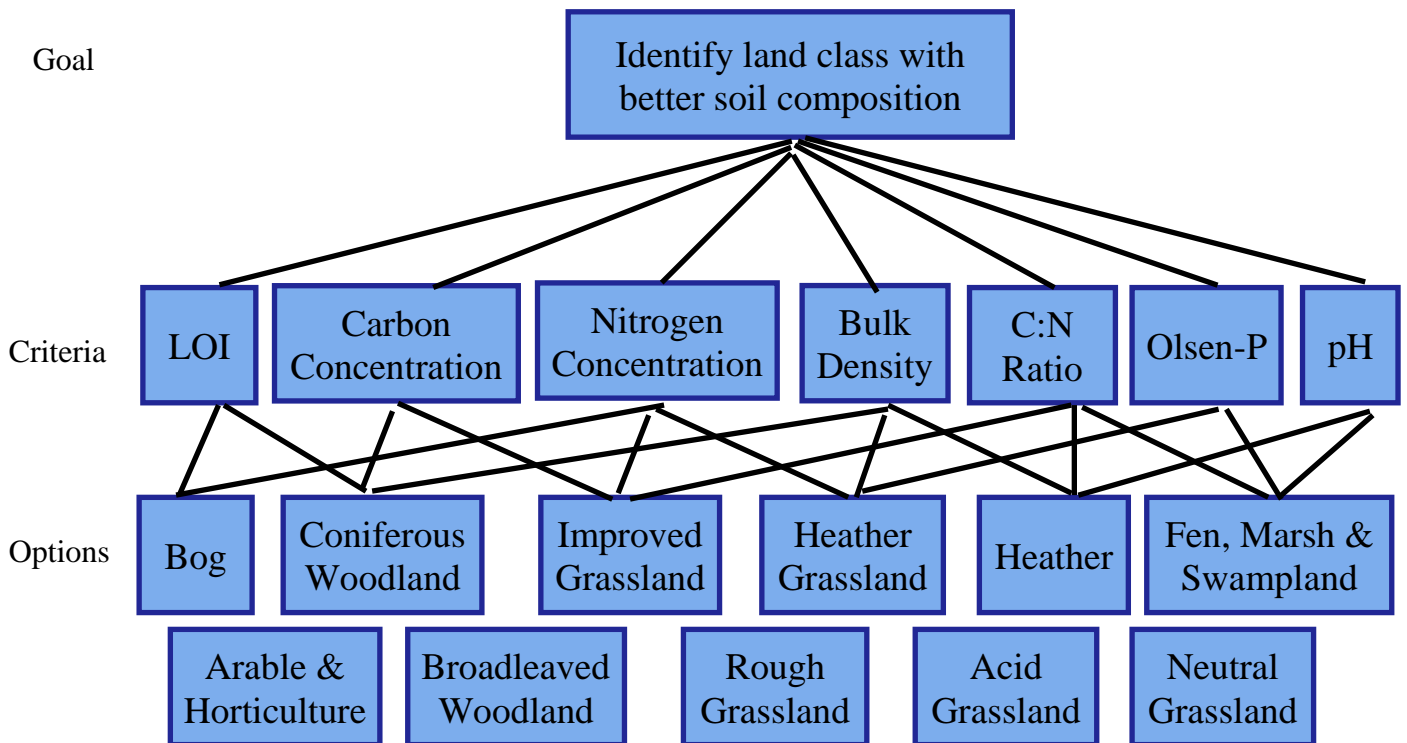


Fig. 1. Decision Framework for AHP

II. Goal

Goal of the model was to identify land across with better soil composition in Scotland.

III. Alternatives (Options)

Suitable alternatives for the model were identified to be the land classes (UKSO LCM Class) across Scotland, namely, Bog, Arable and Horticulture, Coniferous Woodland, Broadleaved Woodland, Improved Grassland, Rough Grassland, Heather Grassland, Acid Grassland, Heather, Neutral Grassland, Fen, Marsh and Swampland.

IV. Criteria

Attributes determining the soil fertility from UKSO datasets were considered to be most suitable for the criteria definition. Attributes identified were Loss-on-ignition, CN Ratio, Carbon Concentration, Nitrogen Concentration, Olsen Phosphorus, Bulk Density and pH levels.

3.3.2.4. Prioritisation, Standardisation, Scoring and Ranking of alternatives

Next steps in the Analytical Hierarchy Process method involves prioritisation and standardisation of criteria, scoring and ranking of alternatives.

I. Prioritisation

Prioritisation was carried out with the use of pairwise comparison matrix where priority for each criterion against the others was determined. To determine priority in AHP, discrete numerical semantic scale is used where value 1 determines equal priority amongst the criteria and higher number determines higher priority of one criterion over another (Dean, 2022). Finally, pairwise comparison matrix results in

weights using below equation that determines importance of the criteria in subsequent calculations.

$$w_j = 1 / \sum \text{values}$$

II. Standardisation & Scoring

Standardisation & Scoring process is required for comparing alternatives, as various criteria (soil attributes) used in the model may have different units of measurement (Dean, 2022). To make the criteria comparable and apply necessary mathematical operations, their values have to be converted to common scale (Dean, 2022). For this model, scale of 0 - 1 was chosen. In order to determine appropriate standardised score for criteria such as Loss-on-ignition (LOI), Carbon Concentration, C:N Ratio and Bulk Density, below mentioned mathematical function was applied. However, standardised score for Nitrogen Concentration, Olsen-Phosphorus and pH level criteria was decided to be set with binary value (either 0 or 1) as these soil attributes (criteria) had an acceptable range of values. In other words, if the soil attribute is within certain range, then it is considered appropriate for the soil with value of 1 otherwise not and value 0 is assigned.

Below mentioned function was used for Loss-on-ignition (LOI), Carbon Concentration, C:N Ratio and Bulk Density criteria.

$$\text{Standardisation Score} = (\text{raw score} - \text{min raw score}) / (\text{max raw score} - \text{min raw score})$$

Specifically, C:N Ratio and Bulk Density scores were reversed because lower values for both of these soil attributes are actually considered better. So, with below

reversal equations higher score was assigned to the at the attribute having lower value.

Standardisation Score for C:N Ratio / Bulk Density = 1- Standardisation Score

III. Ranking

Once scores and weights are identified for each criterion, overall valuation is performed using below function for each criterion with respect to the identified alternatives (Dean, 2022). Subsequently, based on the overall valuation, alternatives are ranked.

$$V(a) = \sum_{j=1}^N w_j \times x_j(a)$$

$x_j(a)$ is a score assigned for j^{th} criterion per alternative (a).

w_j is the weight assigned for j^{th} criterion.

$V(a)$ is the overall valuation function.

3.3.2.5. Identify preferred alternative

Identifying preferred alternative always depends on the available data for the identified criteria and weight of criteria based on their relative importance. Considering the goal of identifying better soil based on soil composition, the alternatives (land classes) are ranked based on overall valuation as discussed previously. As a result, alternatives having highest value receives first rank, and next highest valued alternative receives second rank, so on and so forth. Finally, highest ranking alternative is chosen as best outcome of the model.

3.3.2.6. Discuss the model outcome

Refer '[Results & Discussion](#)' section for model outcome discussion.

CHAPTER 4: Results & Discussion

CHAPTER 4: Results & Discussion

4.1. Fieldwork

Table 1 shows the pH levels measured at all the farms and table 2 shows the survey responses received during the fieldwork. Further, the survey responses were collected from 6 different farmers / farm organisations across Aberdeenshire for total of 12 fields. As shown in table 2, SRUC Tulloch is an organic farm for more than 30 years where cow dung was used as fertiliser which is known to increase pH levels of the soil (Zhang et al., 2020) and no pesticide were being used. As a result, the pH level measured at SRUC Tulloch Arable farm was at 6.8 which is well within acceptable range (5.5 to 8.0).

Field Work Dates	Location	Farming Method	Type of Farm	pH measurements
13/06/23	SRUC Tulloch	Organic	Arable	6.8
13/06/23	SRUC Tulloch	Organic	Grazing	6.4
16/06/23	New Aberdour	Organic	Arable	6.4
16/06/23	New Aberdour	Organic	Grazing	6.7
16/06/23	New Aberdour	Organic	Silage	6.8
26/06/23	SRUC Conventional	Conventional	Arable	5.6
26/06/23	SRUC Conventional	Conventional	Grazing	5.9
26/06/23	SRUC Conventional	Conventional	Silage	6.4

Table 1. Field work at organic and conventional farms.

On the other hand, an arable organic farm in New Aberdour had been applying farmyard manure which is known to significantly improve pH levels of soil (Wang et al., 2023). While in the silage field of the same farm, hen layer manure

Farmer/Business Name	Farming Method	No. of years	Type of Farm	Product	Fertiliser	Pesticide	Type of soil
SRUC Tulloch	Organic	30	Arable	Cereal	Cow Dung	None	Unknown
SRUC Tulloch	Organic	30	Pastoral	Animal Feed	Cow Dung	None	Unknown
B. Irvine/New Aberdour	Organic	5	Arable	Spring Barley	Farm yard manure	None	Sandy Loam
B. Irvine/New Aberdour	Organic	5	Pastoral	Animals	None	None	Sandy Loam
B. Irvine/New Aberdour	Organic	5	Silage	Animal Feed	Hen layer manure	None	Sandy Loam
SRUC Conventional	Conventional	100	Arable	Cereal	N/P/K at 180/67/83 kg/ha	Standard herbicide –(2 applications) Standard fungicide (regime – 3 applications)	Sandy Loam
SRUC Conventional	Conventional	100	Pastoral	Animal Feed	None	None	Sandy Loam
SRUC Conventional	Conventional	100	Silage	Animal Feed	None	None	Sandy Loam
Ian G Smith & partners	Conventional	90	Pastoral /Barely to feed cows	Animals	Nitrogen Phosphate Potassium	Weed killer/fungicide (one/ yr)	Sandy Loam
D. Morrison	Conventional	7	Pastoral /Kale to feed cows	Animals	Cow Dung	No	Sandy, Clay, Loam
Davidson & son	Conventional	100	Grass/livestock	Animals	Cover Crops/ Nitrogen	Roundup (Glifocit e) for weed control	Light sandy loam
	Conventional	100	Arable	Barley, oilseed rape	Nitrogen Phosphate Potassium		Medium light sandy loam

Table 2. Farmer responses to the survey questions.

was being used which is known to neutralise the pH (Balasubramani et al., 2017). When conventional farms are considered, SRUC Conventional arable farm uses Nitrogen, Phosphate and Potassium (NPK) based fertiliser. The NPK fertilisers are known to accelerate acidification process which decreases the soil pH level up to 0.5 unit on average (Tkaczyk et al., 2020). Similar confirming observations were found for pH levels at SRUC Conventional arable farm when pH levels were compared to its organic counterparts. For comparison, other conventional farms mentioned in the table 2 also use NPK fertilisers, however their pH levels could not be obtained from their farms due to lack of accessibility.

If comparison between organic and conventional arable farms is considered, then it can be noticed from the table 1 that the arable organic farms were found to be having higher pH levels near or above mid-6 range whereas conventional arable farm was found to have pH levels around mid-5 due to the reasons discussed earlier. However, larger sample size (number of fieldwork locations) is needed to conclude that organic farms consistently maintain higher pH levels compared to conventional farms. Despite the noticeable differences, pH levels found in conventional farms remain within acceptable range between 5.5 and 8.0 suitable for agriculture (Rust et al., 2000). Additionally, the variety of crops require different levels of pH within the mentioned range (Agricultural Lime Association, 2023). Furthermore, the ammonia volatilisation is not solely dependent on pH levels, it depends on range of other factors such as temperature, moisture, exchangeable cations, fertiliser source and rate of application (Al-Kanani et al., 1991). Hence, pH levels solely could not be a single factor to determine the difference in amount of ammonia released between organic and conventional farming. Additional atmospheric measurements

have to be considered to evaluate the difference in ammonia released between organic and conventional farming.

4.2. Agricultural Region

Reviewing the agriculture in Scotland as per the fig. 2, it is evident that majority of agricultural activities occurs in North East and Southern region (agricultural region— between 200,000m and 450,000m on X axis and 550,00m and 900,000m on Y axis) of Scotland. Noticeably, there are no class 1 agricultural land which could be located across Scotland. However, class 2 agricultural land is found between 300,000m and 400,000m over X axis and between 600,000m and 800,000m over Y axis. Further, majority of agricultural land found in North East and Southern region is class 3 and class 4. Rest of the land across Scotland is categorised with class 5 and above as the region is not identified to be suitable for agricultural activities. As expected, majority of organic and conventional farms identified on the map are found to be in agricultural region of Scotland.

4.2.2. Agricultural Crops (Land Cover Map: Crops)

Visualising the Land Cover Map with Crops raster, it is evident from fig. 3 that majority of the agricultural region across Scotland is grassland, and spring barley is a major crop cultivated across the region. Not in significantly larger area, but potatoes and oilseed rape are also being cultivated in eastern region of Scotland between 300,000m and 400,000m over X axis and 700,000m and 800,000m over Y axis.

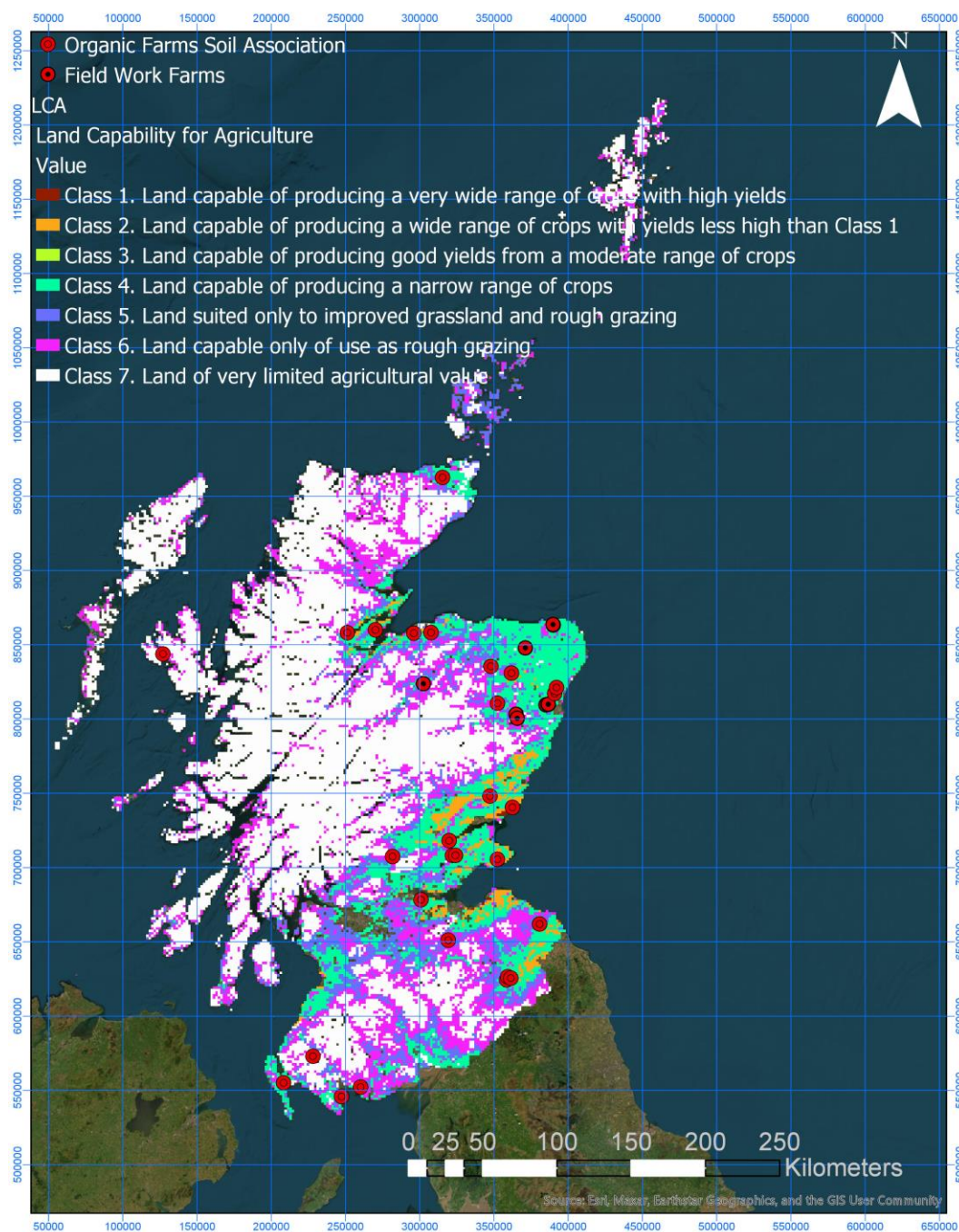


Fig. 2. Field Work Farms and Organic Farms from Soil Association with Land Capability of Agriculture classification in Scotland.

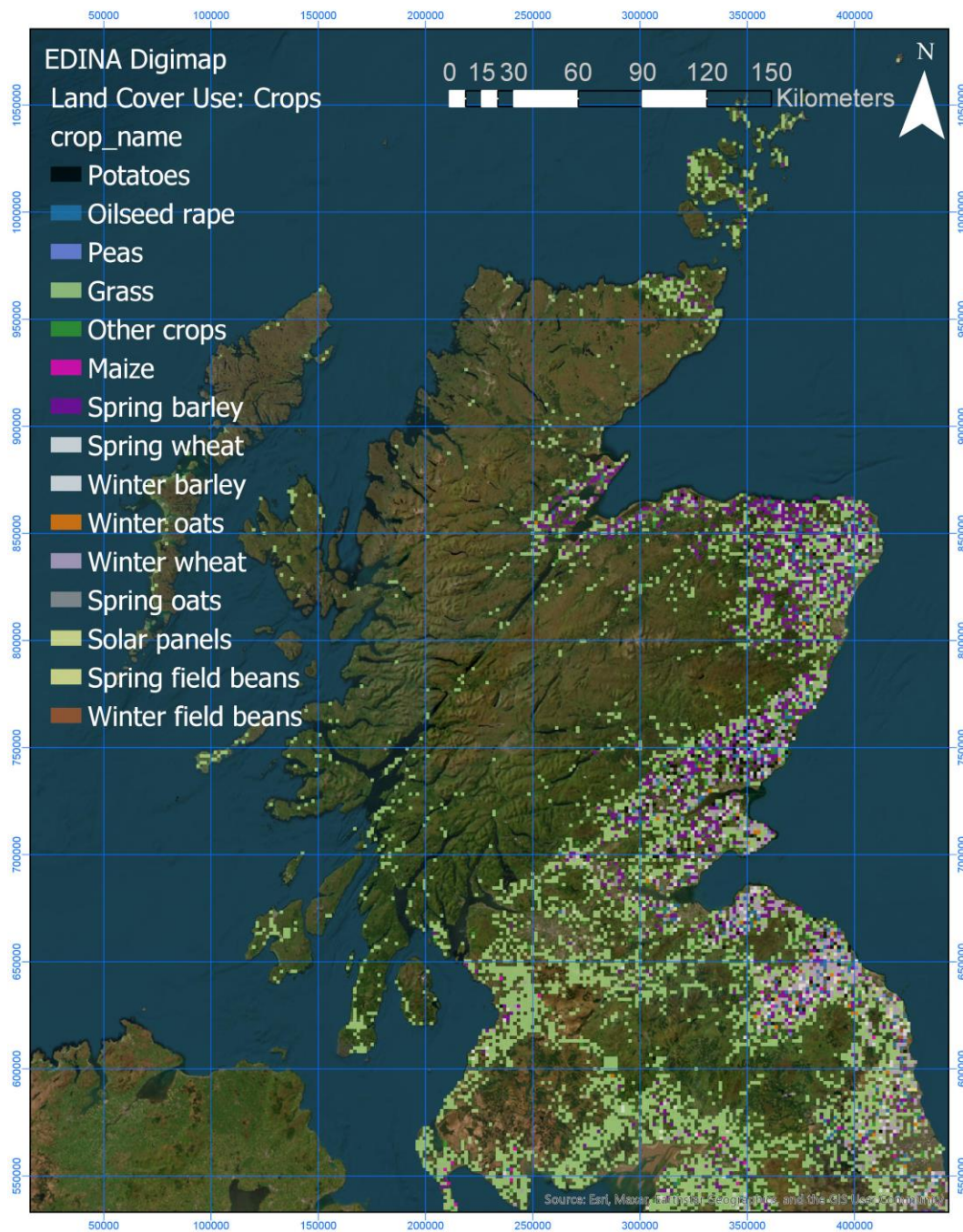


Fig. 3. Range of crops across agricultural region (Land Cover Use: Crops from Edina Digimap)

4.2.3. Agricultural Ammonia Emissions and Organic Farms

The fig. 4a shows most of the highly productive agricultural regions of Scotland (Class 2 to Class 4) identified in previous section has more than one tonne/km² of ammonia emissions whereas rest of Scotland has far lower than 1 tonne/km² of ammonia emission.

With Map Algebra, it was found that 21 out of 29 organic farms (Soil Association) were located where less than 1 tonne of ammonia per square kilometre was released in the atmosphere. This further confirms that the organic farms have comparatively lesser ammonia emission as compared to other agricultural regions in Scotland. For visual comparison of organic farm locations and ammonia emissions, refer fig. 4b.

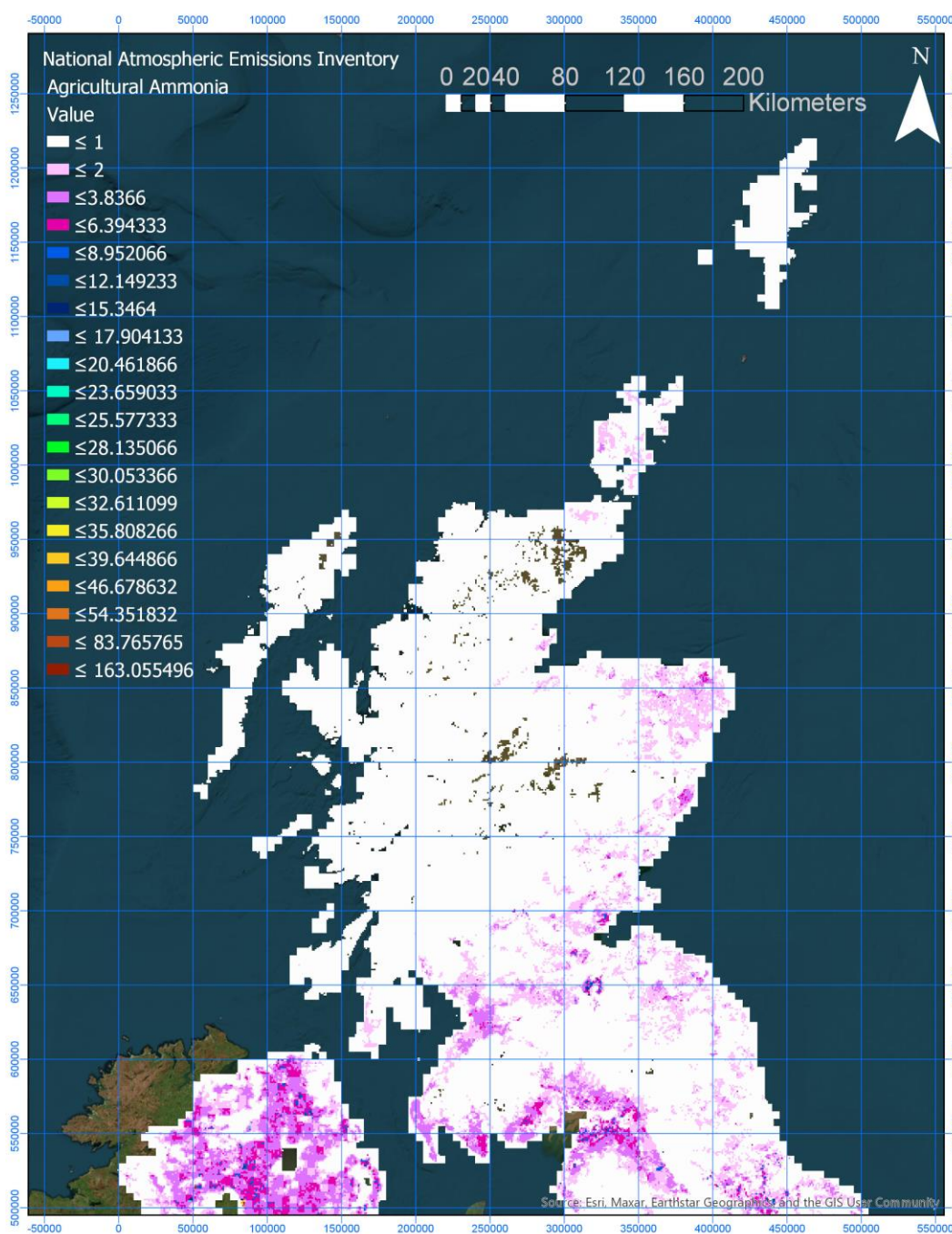


Fig. 4a. Agricultural Ammonia (in tonnes/km²) from National Atmospheric Emissions Inventory.

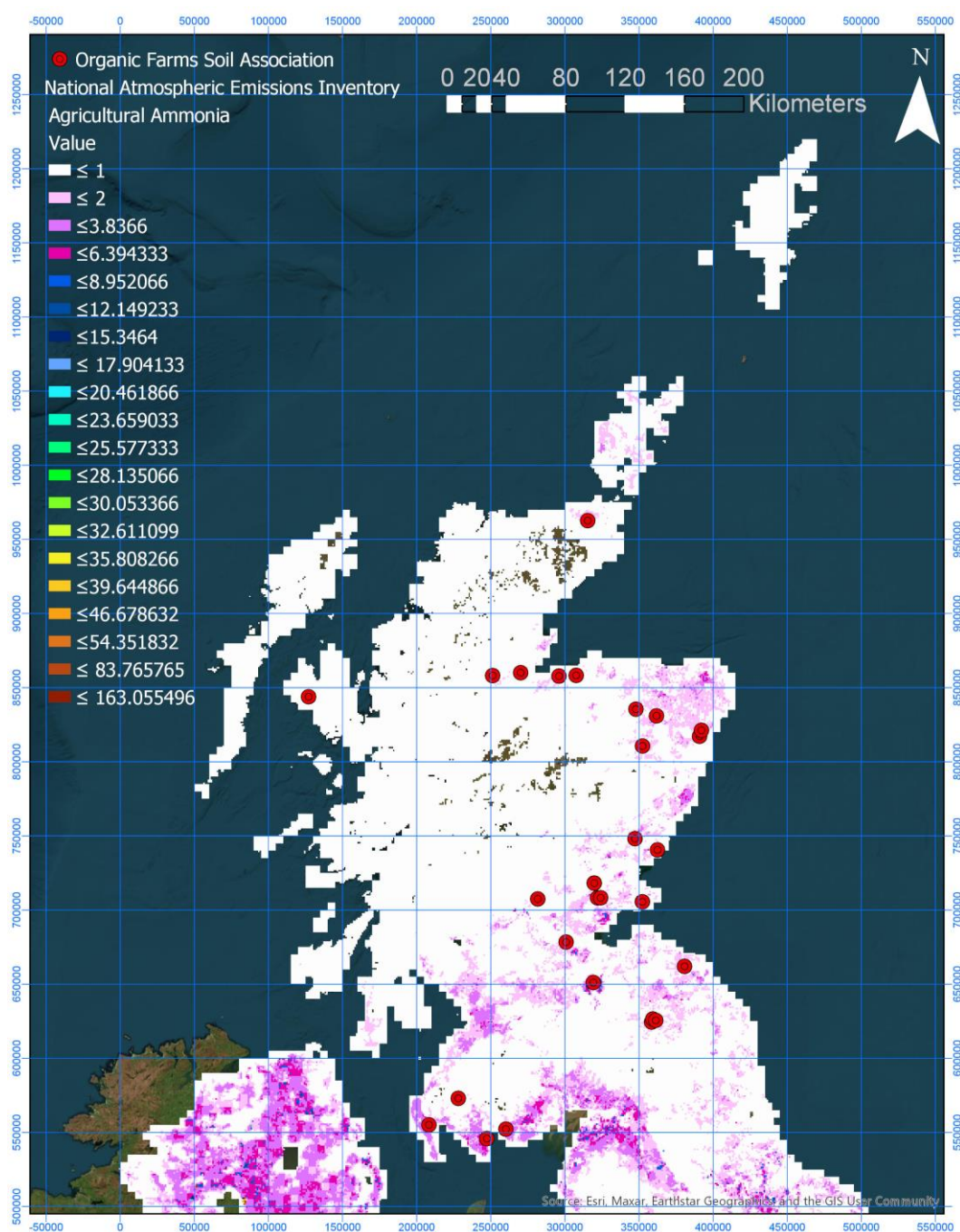


Fig. 4b. Agricultural Ammonia (in tonnes/km²) with Organic Farms (Soil Association).

4.3. Soil Analysis Across Scotland (UKSO)

4.3.1. Loss-on-ignition (LOI)

As the LOI percentage calculated conveys the amount of organic matter the sample had (Robertson S., 2011). As shown in fig. 5, it is evident that the

agricultural region of Scotland has lower (<20.73) organic matter content compared to other regions. Central Scotland (between 200,000m to 350,000m on X axis and 750,000m to 850,000m on Y axis) has moderate level (between 20.73 and 62.18) of organic matter whereas northern and north-western Scotland (between 50,000m to 350,000m on X axis and 900,000m to 1,000,000m on Y axis) has significantly higher (≥ 62.18) organic matter as per the map.

4.3.2. Carbon Concentration

As it is understood that higher the carbon concentration, it is better for agriculture (Pimentel et al., 2014). So, by analysing the carbon concentration raster shown in fig. 6, it can be noticed that carbon concentration in the agricultural region in Scotland is comparatively lower (≤ 100 g/kg) compared to other regions of Scotland (> 100 g/kg). Much higher concentration (> 250 g/kg) of carbon was found in northern and north-western region (between 50,000m to 350,000m on X axis and 900,000m to 1,000,000m on Y axis) of Scotland where agriculture is negligible.

4.3.3. Bulk Density

As it is known that soil with higher bulk density cannot provide enough nutrients to plants (Trace & Save, 2023). So, with further analysis of the raster created using bulk density data as shown in fig. 7, it was observed that the agricultural region of Scotland has higher bulk density (> 0.79 g/cm³) compared to other regions of Scotland (≤ 0.79 g/cm³).

4.3.4. Nitrogen concentration

By reviewing nitrogen concentration raster as shown in fig. 8, it was noticed that agricultural region of Scotland has lower than normal range (< 0.5 %) of nitrogen concentration whereas rest of Scotland is observed to be having better

(within normal range) nitrogen concentration. While, the normal range for total nitrogen percentage is 0.5 to 2.5 (Compost Interpretation, 2023).

4.3.5. C:N Ratio

The preferred range of C:N ratio is 1-15 which results in rapid mineralisation and nitrogen is available for the plants, whereas range between 20-30 is equilibrium state and ratio more than 35 causes microbial immobilisation in soil (Gerald, 2019). Based on that, C:N Ratio raster was reviewed as shown in fig. 9. It was evident that the agricultural region in Scotland has lower (≤ 15) carbon to nitrogen ratio compared to other regions of Scotland. Western Scotland (between 100,000m and 300,000m on X axis and 650,000m to 850,000m on Y axis) has CN ratio between 15 and 20, whereas central Scotland (between 250,000m to 350,000m on X axis and 750,000m and 850,000m on Y axis) and north western Scotland (between 150,000m to 250,000m on X axis and 850,000m to 950,000m on Y axis) has CN ratio between 20 and 24. Although agricultural region has expected carbon-to-nitrogen ratio, however other regions still have potential to improve CN ratio from equilibrium state to rapid mineralisation state.

4.3.6. Olsen-Phosphorus

The expected range of Olsen Phosphorus in soil which is between 10 to 40 mg/kg (Qihua et al., 2020). Considering that, the Olsen Phosphorus raster was reviewed as shown in fig. 10, it is apparent that some areas of agricultural region in Scotland has Olsen-P within expected range, whereas the other areas of the same region has significantly higher (> 40) Olsen-P content. However, most of the Scotland beyond agricultural region has Olsen-P measurements within the expected range.

4.3.7. pH levels:

The optimum pH range is expected to be between 5.5 and 8.0 (Rust et al., 2000). With that, pH level raster was reviewed as shown in fig. 11. From the raster, it can be asserted that pH level within agricultural region of Scotland ranges between 6 and 8 which is within expected range for agricultural activities. Whereas, other regions of Scotland are highly acidic as the pH levels are below 5.5 as shown in the fig. 11.

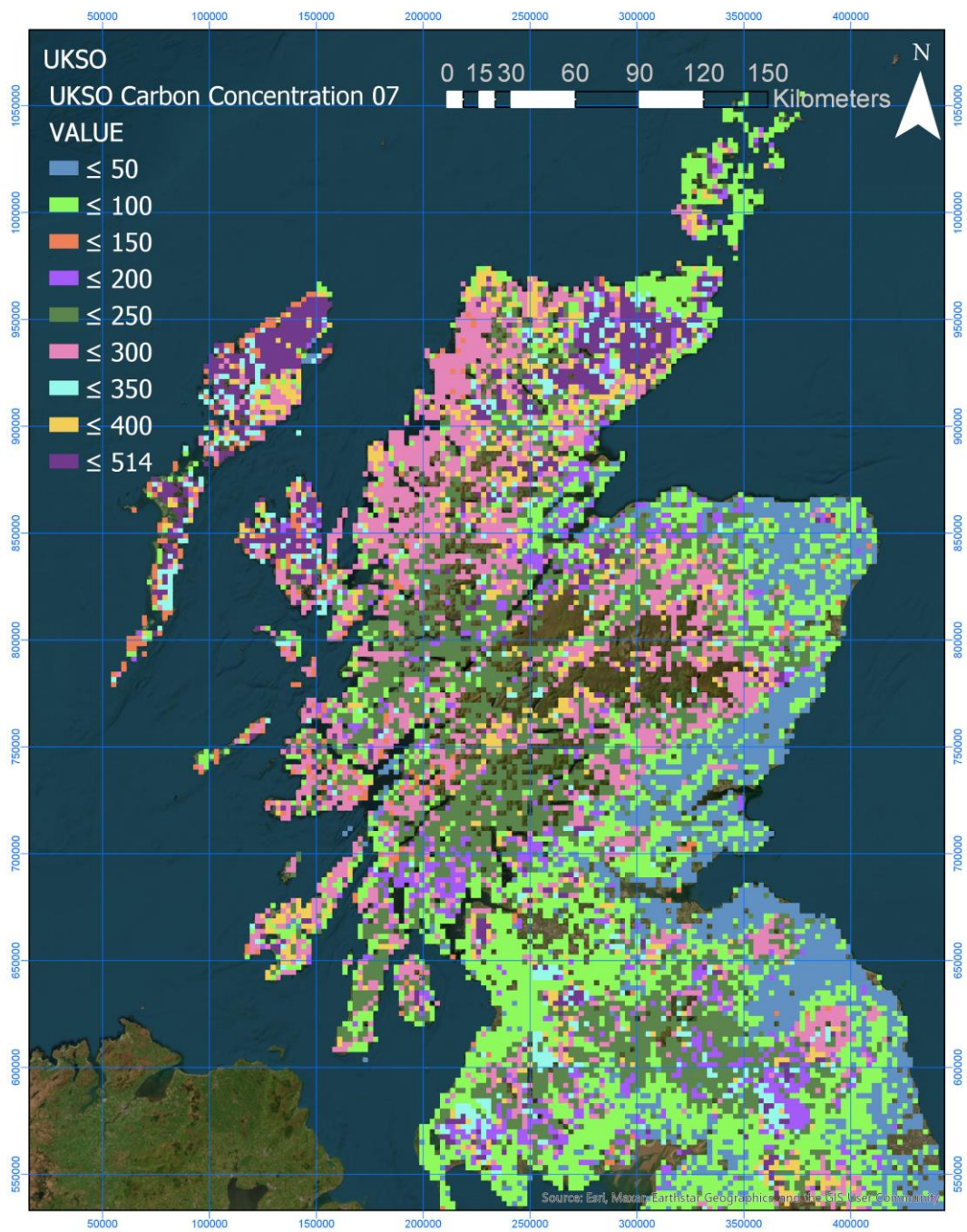


Fig. 6. Soil Carbon Concentration (UKSO)

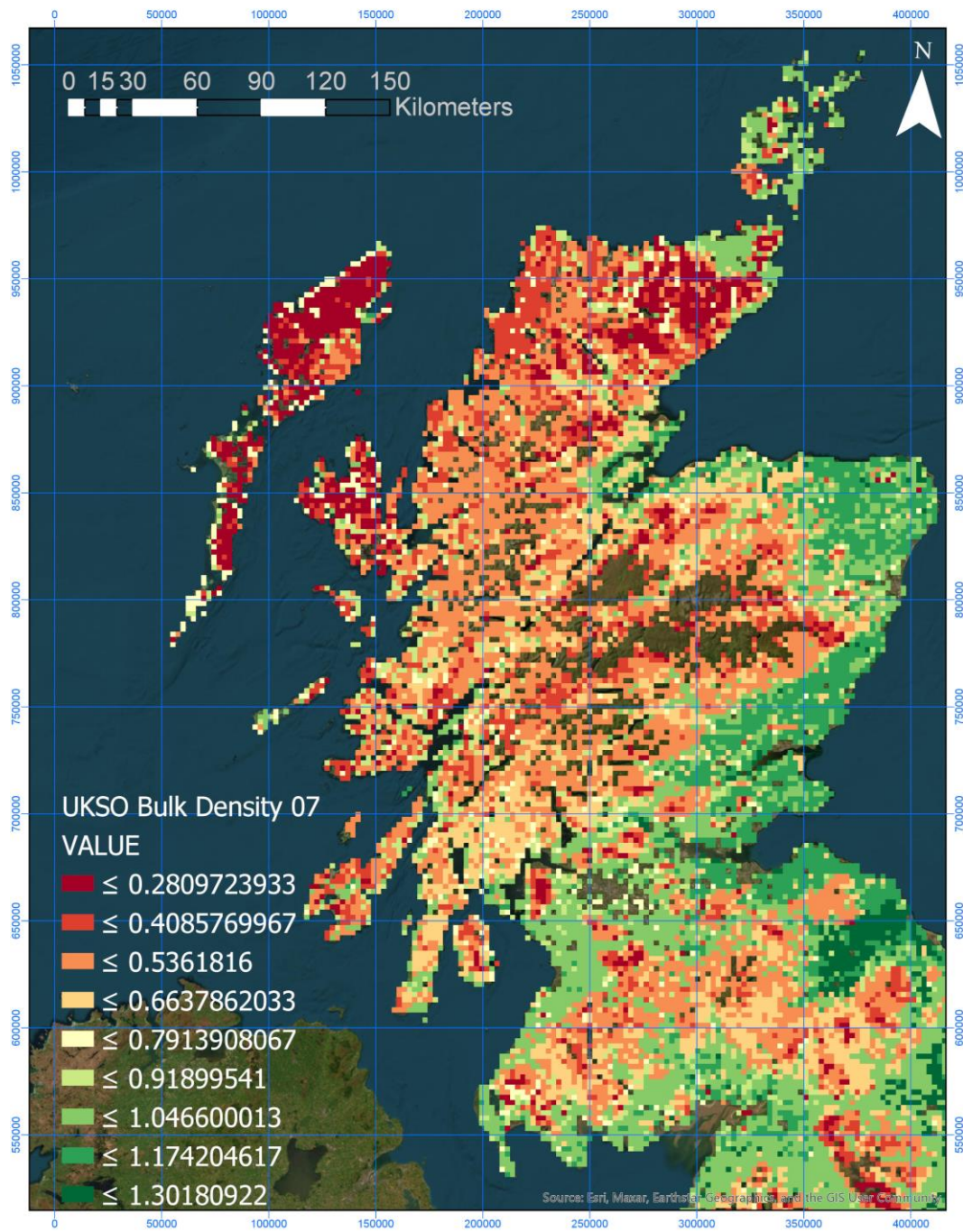


Fig. 7. Soil Bulk Density (UKSO)

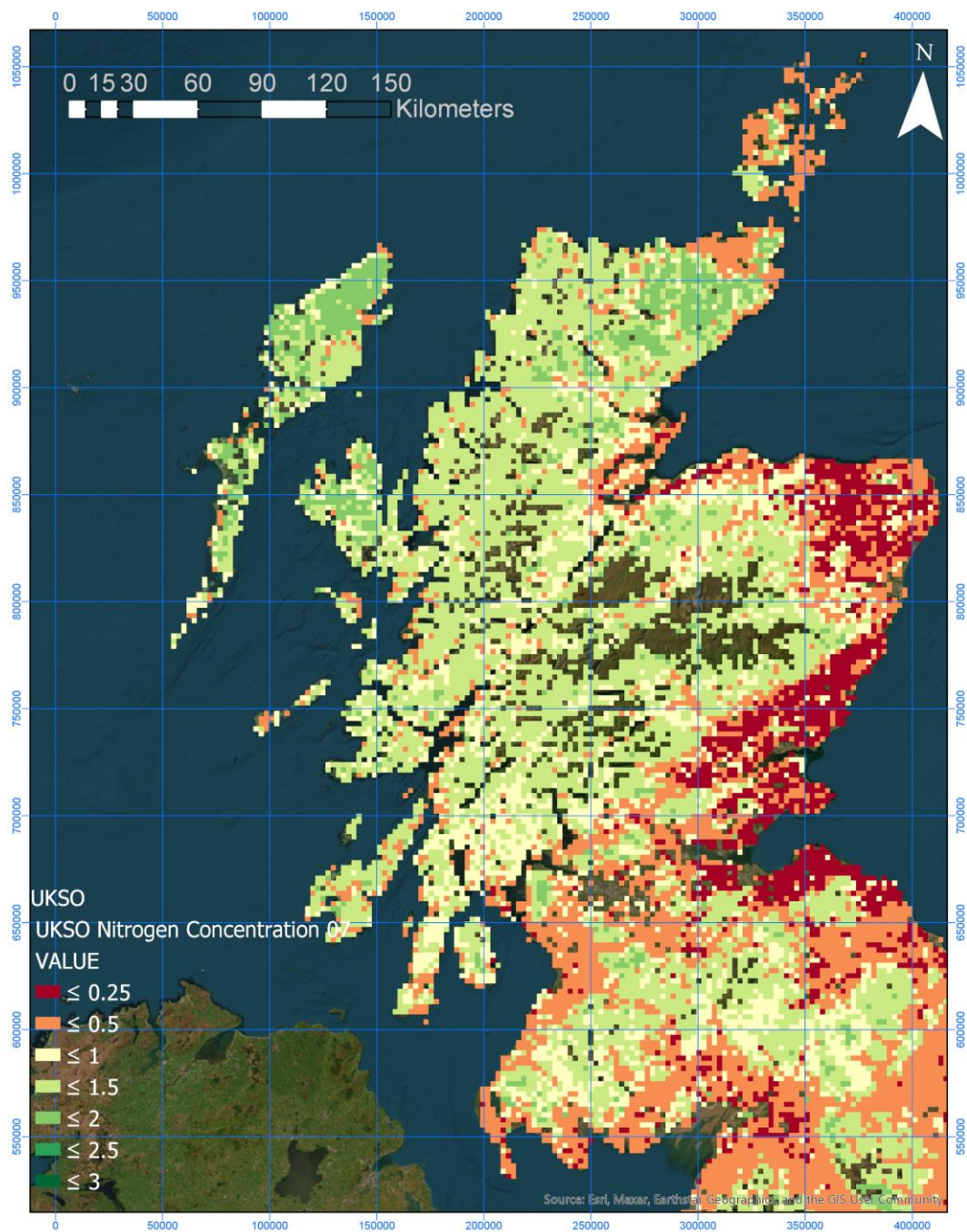


Fig. 8. Soil Nitrogen Concentration (UKSO)

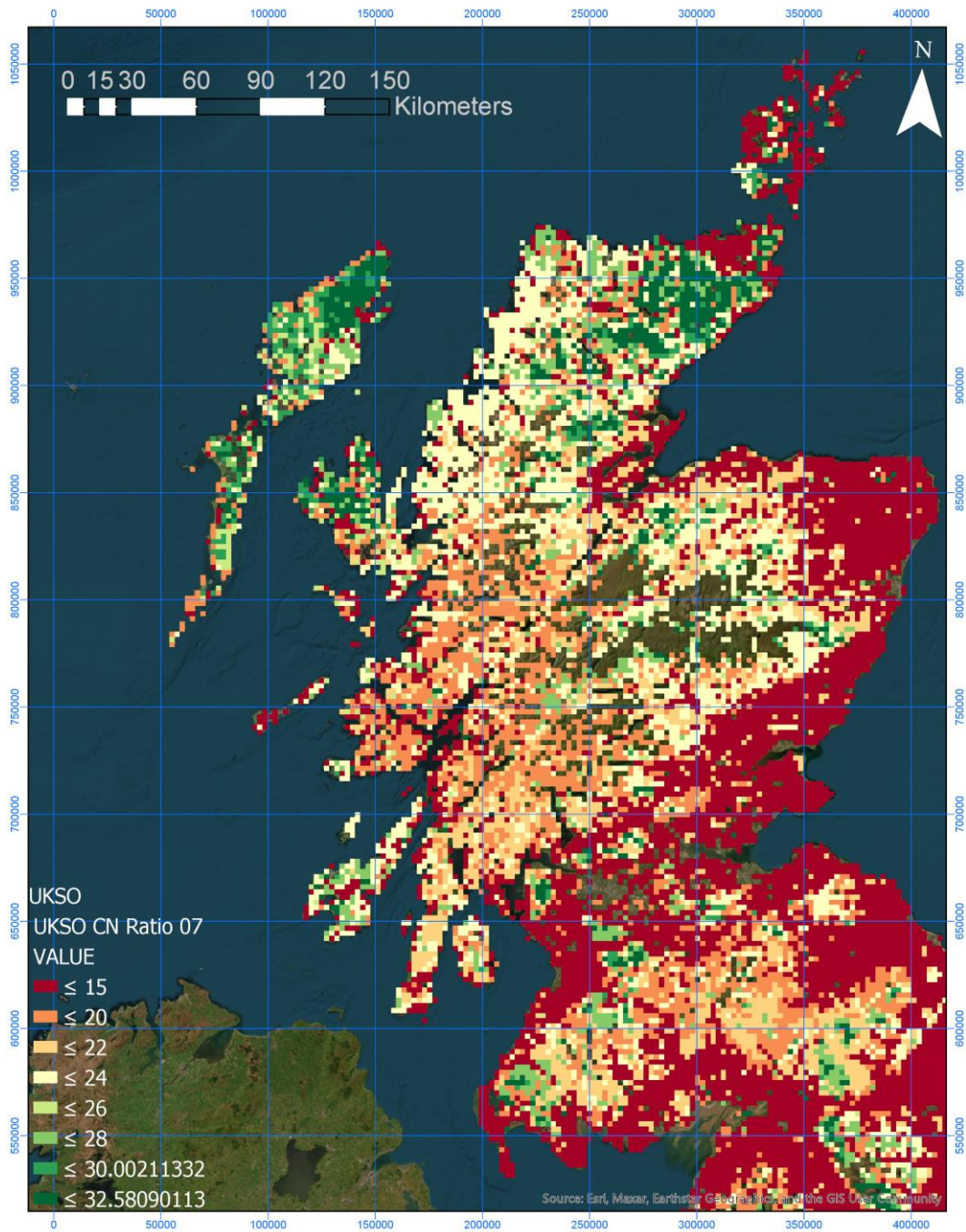


Fig. 9. Soil C:N Ratio (UKSO)

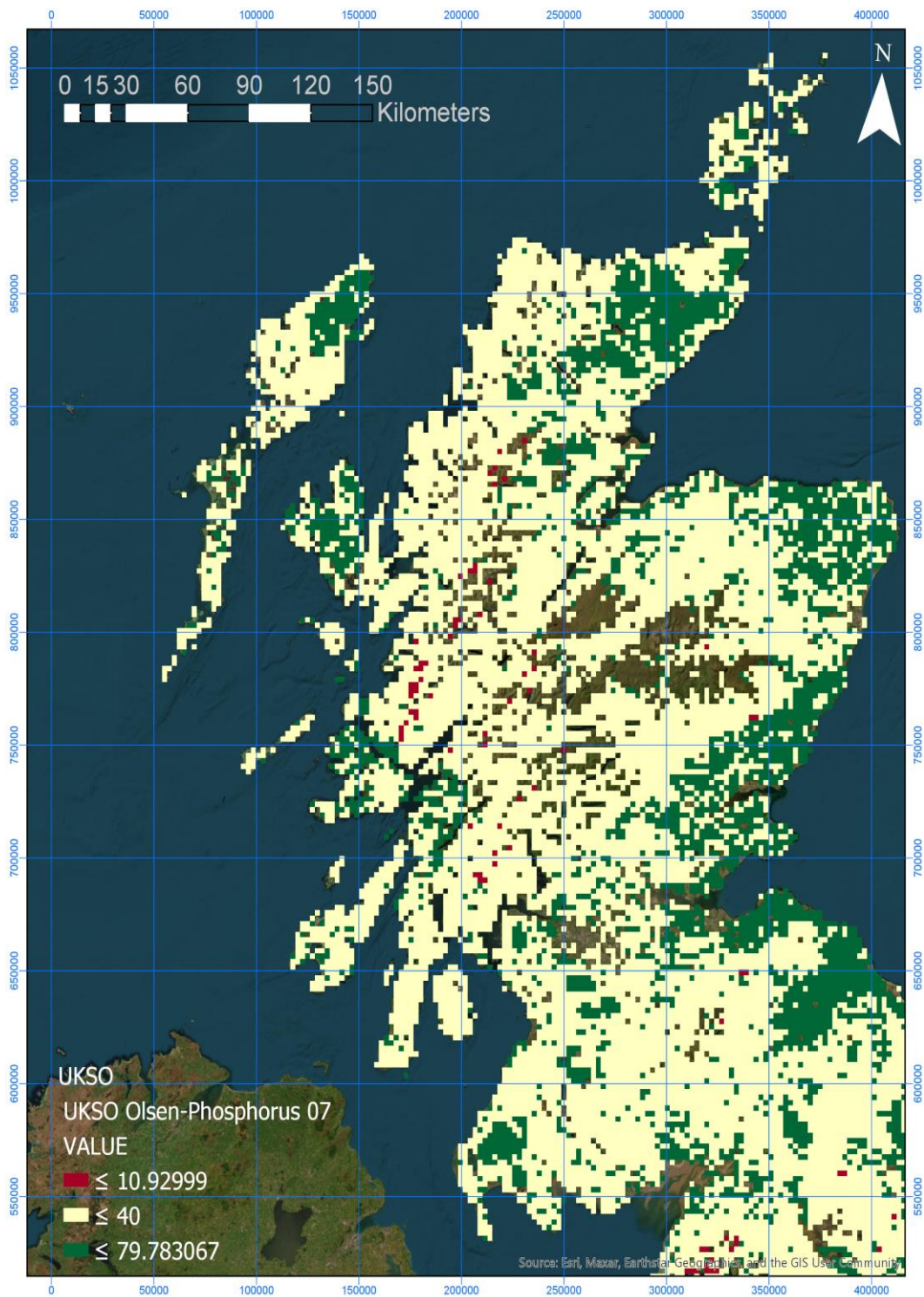


Fig. 10. Soil Olsen-Phosphorus (UKSO)

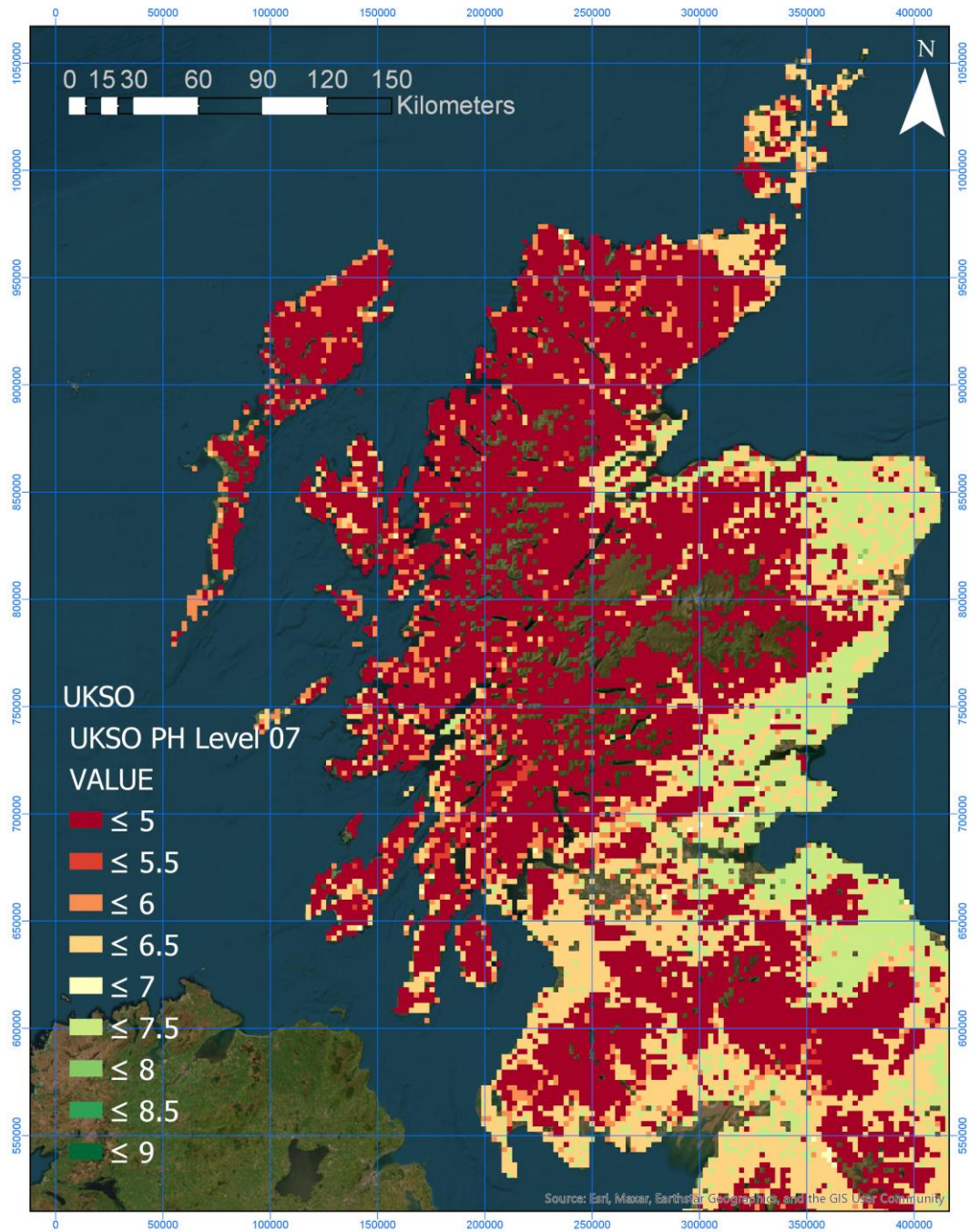


Fig. 11. Soil pH levels (UKSO)

4.3.8. Soil comparison within Agricultural Region (Organic Farms & Others)

With the use of Spatial Join feature from ArcGIS Pro, two sets of feature classes were created. One with UKSO soil attributes joining with organic farms (Soil Association) across Scotland and another with UKSO soil attributes joining with agricultural region of Scotland. The purpose of creating these feature classes was to collect statistics from their respective attribute tables as shown in table 3.

Soil Attribute	Organic Farms (Mean)	Agriculture Region (Mean)
Bulk Density	0.97	0.94
C:N Ratio	12.40	12.92
Carbon Concentration	63.53	70.45
LOI	10.87	12.12
Nitrogen Concentration	0.38	0.45
Olsen Phosphorus	36.83	35.73
pH levels	6.2	6.18

Table 3. Average soil attributes comparison between organic farms and entire agricultural region in Scotland.

As it can be noticed from table 3, and fig. 12 as well as fig. 13 that there are no significant differences between organic farms and other farms across the agricultural region in Scotland for range of soil attributes (LOI, Carbon Concentration, Nitrogen Concentration, Bulk Density, C:N Ratio, Olsen Phosphorus, and pH levels). This suggests that organic farms can also be maintained as good as conventional farms with appropriate soil maintenance.



Fig. 12. Soil attributes of Organic Farms

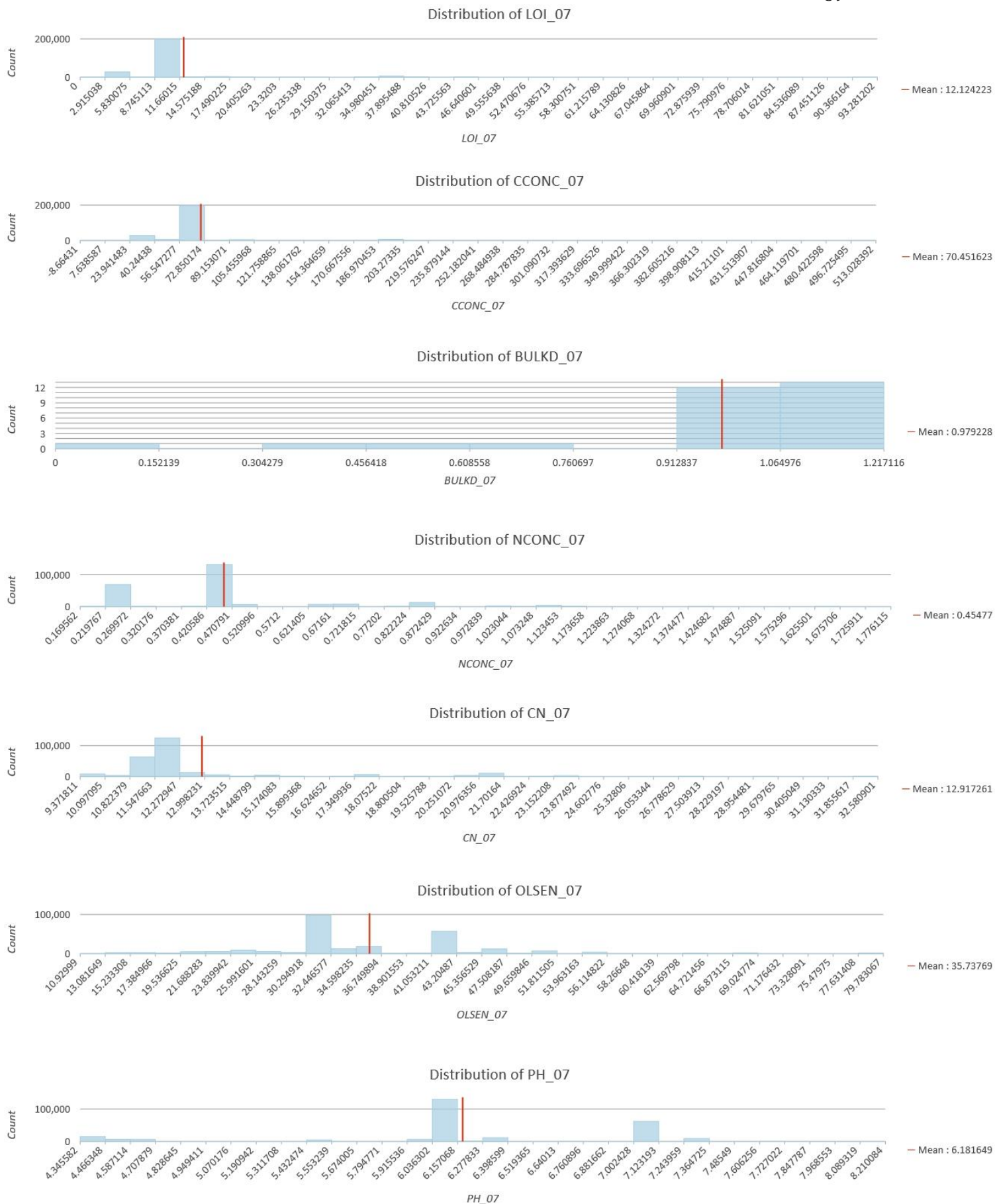


Fig. 13. Soil attributes of entire agricultural region in Scotland

4.3.9. Soil Evaluation & comparison between agricultural & other regions (UKSO)

Several important soil properties were analysed in previous sections where the importance of loss-on-ignition, carbon concentration, bulk density, nitrogen concentration, C:N Ratio, Olsen-P, and pH levels were highlighted. Amongst all the properties, agricultural region has high C:N ratio, even though carbon and nitrogen concentration as well as Olsen-P levels were found to be better in other regions. As carbon, nitrogen and phosphorus are macronutrients which gets absorbed by plants from soil (Morgan et al., 2013), it could leave the soil in the agricultural region deficient of these nutrients which normally gets fortified through the use of fertilisers for better crop yield. As a result, optimum pH levels could be observed. However, other regions have higher LOI, carbon and nitrogen concentration, and lower bulk density, which suggests other regions of Scotland has better soil composition.

4.4. UKSO Land Cover Map Classes

Reviewing the raster created using LCM class field from UKSO datasets, it can be noticed from fig. 14 that the agricultural region is classified as Arable and Horticulture and Improved Grassland. Whereas, northern and north-western region can be recognised mostly as Bog, western region (between 150,000m to 250,000m on X axis and 700,000m to 850,000m on Y axis) is mostly Acid Grassland. Central Scotland (between 250,000m to 350,000m on X axis and 750,000m and 850,000m on Y axis) is classified with mix of Coniferous Woodland, Bog, and Heather Grassland. Southern region (between 200,000m and 450,000m on X axis and 550,000m to 700,000m on Y axis) is mix of Arable and Horticulture, Improved Grassland, Coniferous Woodland, and Acid Grassland.

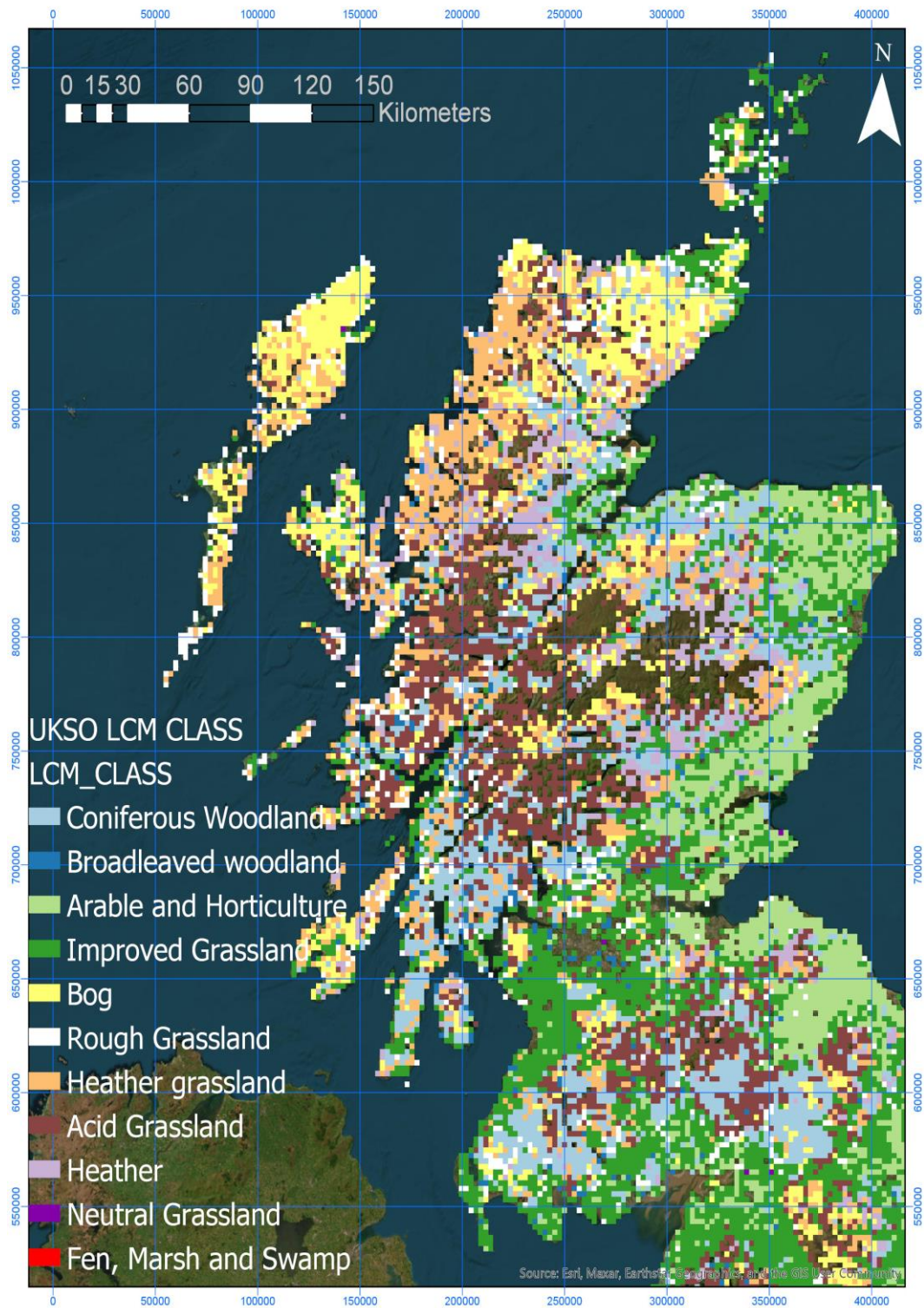


Fig. 14. Land Classes in Scotland (UKSO)

4.5. Heavily Used Pesticides

After pesticides data was sorted, organised by location and imported into ArcGIS Pro as a shape file, it was then converted to raster as shown in fig. 15. It can be noticed from the figure that most of the pesticide use occurs mainly in agricultural region of Scotland. Specifically, the use of pesticide is moderately

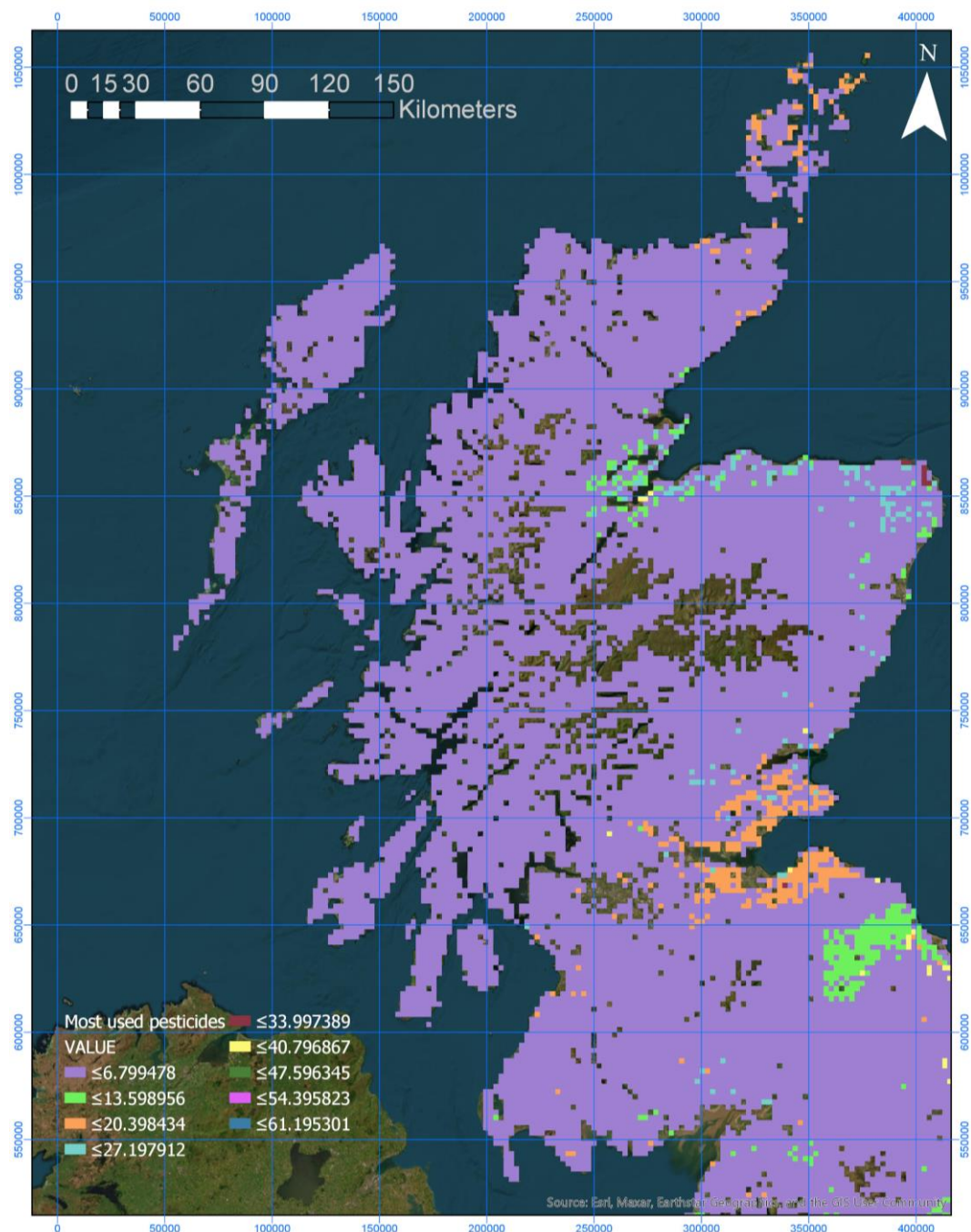


Fig. 15. Heavily Used Pesticides (UKCEH)

heavy (up to 33 kg/km²) in northeast region (between 250,000m to 450,000m on X axis and 800,000m to 900,000m on Y axis). On the other hand, the use of pesticide is moderate (13-20 kg/km²) in south-eastern region (between 250,000m to 400,000m on X axis and 650,000m to 750,000m on Y axis). Comparatively, low levels of pesticide use (≤ 13 kg/km²) was found in rest of Scotland.

4.6. Application of Multi-criteria Analysis Model using Analytical Hierarchy

Process

Land Classes	LOI Avg. %	Carbon Concentration (Avg. g/kg)	N Concentration (Avg. %)	Bulk Density (Avg. g/cm ³)	C:N Ratio (Avg.)	Olsen-P (Avg. mg/kg)	pH (Avg. g.)
Bog	70.68	389.80	1.45	0.32	26.70	29.99	4.65
Arable and Horticulture	5.87	35.95	0.269	1.16	11.42	46.26	7.36
Coniferous Woodland	36.38	202.74	0.88	0.56	21.02	27.78	4.66
Broadleaved Woodland	16.59	94.85	0.67	0.74	14.89	25.58	5.80
Improved Grassland	10.89	63.79	0.48	0.94	11.84	34.41	6.38
Rough Grassland	13.36	77.24	0.5	0.87	13.05	24.58	6.23
Heather Grassland	46.92	260.23	1.07	0.42	23.18	20.76	4.70
Acid Grassland	40.01	222.55	1.16	0.52	17.52	18.30	4.80
Heather	46.80	259.56	1.07	0.42	23.17	20.68	4.66
Neutral Grassland	13.51	78.03	0.5	0.87	13.27	23.32	6.06
Fen, Marsh and Swampland	37.84	210.72	0.99	0.51	17.24	19.38	5.60

Table 4. Average values of soil attributes (criteria) grouped by land classes (alternatives).

As the model uses land classes as alternatives and soil composition attributes as criteria, table 4 shows the average values of criteria grouped based on respective land classes derived from UKSO datasets.

4.6.1. Pairwise Comparison Matrix

As the model needs pairwise comparison matrix, the table 5 below shows the matrix which uses numerical scale from 1 to 7 to determine priorities for each criterion. As per the specification, if higher value is assigned to a criterion then the criterion has higher importance compared to the other. If value of 1 is assigned then criteria in comparison has equal priority. Eventually, the matrix results in weights for each criterion for subsequent use.

Criteria	pH (Avg)	Olsen-P (Avg)	BulkD (Avg)	CN Ratio (Avg)	NCON C (Avg)	CCON C (Avg)	LOI (Avg)	Weights = $1/\sum \text{columns}$
pH (Avg)	1	2	3	4	5	6	7	0.04
Olsen-P (Avg)	1/2	1	2	3	4	5	6	0.05
BulkD (Avg)	1/3	1/2	1	2	3	4	5	0.06
CN Ratio (Avg)	1/4	1/3	1/2	1	2	3	4	0.09
NCONC (Avg)	1/5	1/4	1/3	1/2	1	2	3	0.14
CCONC (Avg)	1/6	1/5	1/4	1/3	1/2	1	2	0.22
LOI (Avg)	1/7	1/6	1/5	1/4	1/3	1/2	1	0.39

Table 5. Pairwise comparison matrix to prioritise criteria (UKSO soil attributes).

The table 5 shows how each criterion such as LOI, Carbon Concentration (CCONC), Nitrogen Concentration (NCONC), Carbon-to-Nitrogen Ratio (CN Ratio), Bulk Density (BulkD), Olsen-Phosphorus (Olsen-P), and pH compares to one another. In the table, LOI is given the priority of 7, Carbon Concentration is 6, Nitrogen Concentration is 5, CN Ratio is 4, Bulk Density is 3, Olsen Phosphorus is 2 when compared with pH. LOI is given highest priority because it is considered a strong indicator of soil fertility as it determines total percentage of overall organic matter present in the soil. Carbon concentration is given next highest priority as it determines total organic matter in the soil. Nitrogen concentration is given next level of priority as nitrogen is important for plant growth, however it can be replenished in the soil through fertilisers. CN Ratio is next in the priority as this ratio determines the amount of nitrogen that will be available for plant growth. Bulk Density follows next as it indicates the degree to which the soil compacted. Next one is Olsen-Phosphorus as it determines the phosphorus use efficiency, however phosphorus can also be replenished. Also, pH level is given lowest priority as it can be adjusted with fertilisation. Finally, weights are determined for each criterion using the equation mentioned on the column header.

4.6.2. Standardisation & Scoring

All criteria have their own unit of measure, some are measured in percentage while others are measured in grams per kilogram, grams per centimetre cube or milligram per kilogram. This makes comparison of criteria difficult in the model, hence all the criteria are needed to be standardised to same scale. For standardisation, all the criteria are assigned with range of values between 0 and 1 as shown in table 6 using standardisation equation defined in methodology section. Note that nitrogen concentration, Olsen Phosphorus and pH are given numeric score

of boolean values (either 0 or 1) despite these criteria having range of numerical values already. This was done because these criteria had an acceptable range of values and values beyond the acceptable range were considered inappropriate for soil quality.

Alternatives	Criteria						
LCM Classes	LOI (Avg)	CCONC (Avg)	NCONC (Avg)	CN Ratio (Avg)	BulkD (Avg)	Olsen-P (Avg)	pH (Avg)
Bog	1.00	1	1	0.00	1.00	1	0
Arable and Horticulture	0.00	0	0	1.00	0.00	0	1
Coniferous Woodland	0.47	0.47	1	0.37	0.71	1	0
Broadleaved Woodland	0.17	0.17	1	0.77	0.50	1	1
Improved Grassland	0.08	0.08	0	0.97	0.26	1	1
Rough Grassland	0.12	0.12	1	0.89	0.35	1	1
Heather Grassland	0.63	0.64	1	0.23	0.88	1	0
Acid Grassland	0.53	0.53	1	0.60	0.76	1	0
Heather	0.63	0.63	1	0.23	0.88	1	0
Neutral Grassland	0.12	0.12	1	0.88	0.35	1	1
Fen, Marsh and Swampland	0.49	0.49	1	0.62	0.77	1	1

Table 6. Standardised scores are assigned to each criterion.

Further reviewing the standardisation table 6, it was noticed that both LOI and Carbon Concentration criteria have received identical scores even though both the attributes have different sets of original values. The reason for both the criteria to receive identical score was that the carbon concentration values are derived values from Loss-on-ignition by multiplying with the factor of 0.55 (Henry et al., 2012a). Thus, Carbon Concentration criterion could be eliminated as it would not affect the outcome of the model due to elimination.

Alternatives	Criteria						v(a)	Rank
	wj × xj(a)	LOI (Avg)	NCONC (Avg)	CN Ratio (Avg)	BulkD (Avg)	Olsen-P (Avg)		
Bog	0.39	0.14	0.00	0.06	0.05	0.00	0.63	1
Arable and Horticulture	0.00	0.00	0.09	0.00	0.00	0.04	0.13	11
Coniferous Woodland	0.18	0.14	0.03	0.05	0.05	0.00	0.44	6
Broadleaved Woodland	0.06	0.14	0.07	0.03	0.05	0.04	0.38	7
Improved Grassland	0.03	0.00	0.09	0.02	0.05	0.04	0.22	10
Rough Grassland	0.04	0.14	0.08	0.02	0.05	0.04	0.37	8
Heather Grassland	0.24	0.14	0.02	0.06	0.05	0.00	0.50	3
Acid Grassland	0.20	0.14	0.05	0.05	0.05	0.00	0.49	5
Heather	0.24	0.14	0.02	0.06	0.05	0.00	0.50	4
Neutral Grassland	0.05	0.14	0.08	0.02	0.05	0.04	0.37	9
Fen, Marsh and Swampland	0.19	0.14	0.06	0.05	0.05	0.04	0.51	2

Table 7. Valuation of alternatives based on scores and weights.

4.6.3. Ranking

After criteria are standardised and weights for each criterion are determined, overall valuation $v(a)$ for each alternative is performed as shown in table 7. The overall valuation equation is defined in the methodology section.

4.6.4. Model Outcome & Preferred Alternative

Based on the order of overall valuation outcome from highest to lowest, alternatives are ranked. As the overall valuation of an alternative depends on how much each individual criterion contributes to it based on criteria weight and standardised value. Thus, selection of required set of attributes and their correct prioritisation becomes utmost important. Considering the goal was to find better soil composition across Scotland which required a selection of soil attributes such as LOI, Nitrogen concentration, CN Ratio, Bulk Density, Olsen Phosphorus and pH levels based how essential they are for soil fertility. Thus, it can be understood that the final rank which determines the preferred outcome has directly dependency on the scores and priority (weights) of individual criteria. Based on the overall valuation and rank, Bog land class alternative was found to have ranked better as LOI, Nitrogen Concentration, Bulk Density and Olsen-Phosphorus values are higher for Bog compared to others. Fen, Marsh and Swampland was second in the rank as it was found to be better in combination with LOI, Nitrogen Concentration, CN Ratio, Bulk Density and Olsen Phosphorus.

It is important to note that the model is not attempting to predict which land is more suitable for agriculture, instead it is simply focussed on finding better soil by considering the soil composition attributes. Usually, Bog is found to be rich in organic matter and stores high amount of carbon (Shultz, 2018), hence this alternative got ranked higher than others. On the other hand, Bogs are naturally

acidic too. Thus, pH levels score for Bog was 0. However, as the pH level criteria had lowest priority, so it did not affect the selection of Bog as the preferred alternative because the pH levels can be neutralised with external applications (Rust et al., 2000).

CHAPTER 5: Conclusion

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While observing difference in pH between organic and conventional arable farms during fieldwork, the conventional farm was noticeably lower by up to 1.0 pH which could be attributed to the usage of NPK based fertilisers as they are known to accelerate acidification process of soil (Tkaczyk et al., 2020). However, more number of observations are recommended as similar results could be expected in other farms due to the practice of using NPK fertilisers. Also, the difference in pH could not completely be directly attributed to the difference in ammonia emission. Hence, further geospatial analysis was also required.

During geospatial analysis, agricultural ammonia and organic farms data received from Soil Association were compared where emissions of 21 out of 29 farms were found to have less than 1 tonne per sq. km of ammonia emissions while most of the agricultural region in Scotland was found to have higher than 1 tonne per sq. km of ammonia emissions. This finding further confirmed that the difference of ammonia emissions could be attributed to organic method of farming.

Further, comparison of soil composition between organic farms and rest of the agricultural region was performed considering LOI, Carbon Concentration, Nitrogen Concentration, Olsen-Phosphorus, C:N Ratio, Bulk Density, and pH level data from UKSO datasets. During comparison, no significant difference in average soil composition was observed between organic and conventional farms too. This highlighted the fact that organic farms and conventional farms could be similarly maintained while contributing to lower ammonia emissions.

Furthermore, the multi-criteria Analysis based (AHP method) model was created to identify better soil composition across Scotland using LOI, Nitrogen

Concentration, Olsen-Phosphorus, C:N Ratio, Bulk Density, and pH which resulted in Bog land class was found to be better due to being rich in organic matter and carbon content (Shultz, 2018). However, the model does not determine if a land class could be suitable for agriculture or not as it only focusses on identifying better soil composition. Finally, heavily used pesticides were also evaluated across Scotland which showed that the agricultural region of Scotland was found to have low to moderately heavy use of pesticides.

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APPENDICES

APPENDICES

APPENDIX I: pH measurement tools and technique

pH levels were measured with pH meter and distilled water acquired from the School of Geoscience at University Of Aberdeen. pH meter was required to be calibrated before measurements could be recorded during the field work. Hence, based on the calibration settings of the metre, buffer solutions for pH level 4 and pH level 7 were purchased. Subsequently, before every field work visit, pH meter was verified to be correctly calibrated with buffer solutions to ensure pH readings were accurate with measurement error of ± 0.1 unit.

Procedure followed for pH measurement:

During each fieldwork visits following procedure was followed:

1. Soil samples from the field were collected in a container (pre-rinsed with distilled water).
2. Distilled water was added to the container having soil sample with 3:1 ratio.
3. Content of the container were mixed well to break the lumps of soil sample to form an evenly mixed solution.
4. Sensor of the pH meter was cleaned with distilled water to remove any dirt or soil residues which may have remained from previous tests.
5. pH meter was dipped into the solution to measure pH levels. The readings on the meter were allowed to settle before the final readings were recorded.

APPENDIX II: How the survey was conducted?

Based on the relevance of the field work, the survey questions were identified. The questions were asked to know Farmer Name/Business Name, Email, Phone Number, Postal Code (to identify location of the farm), Address, Method of farming (Organic/Conventional), Type of farm (Arable/Pastoral/Mixed), Fertiliser product used, Pesticide product used, Type of soil, Size of the farm. These questions were not only useful to understand the differences of farming practices between organic and conventional farms but also helpful to acquire location information essential for geospatial representation and analysis.

The survey was conducted using following methods.

1. Survey was created with list of questions using [survey123.ArcGIS.com](https://survey123.arcgis.com)
 - Link to the survey: <https://arcg.is/1fuOb5>
2. Some survey responses were also collected over an email.
3. Other responses were collected over the phone as well.

Although, chosen method of survey was to use Survey123, however other methods such as email and phone calls were used depending on farmer preferences.

APPENDIX III: CSV to Shape file using Convert Coordinate Notation

Once fieldwork data and organic farms data from Soil Association were available with coordinates (longitude and latitude) in CSV file, Convert Coordinate Notation tool from ArcGIS Pro was used to not only convert coordinates from GSC WGS 1984 to British National Grid coordinate system, but also to convert the CSV into shape file for geospatial analysis.

Convert Coordinate Notation tool:

Convert Coordinate Notation is one of the tools present under ‘Data Management’ toolbox in the ‘Geoprocessing Tools’ of ArcGIS Pro. The tool accepts parameters such as Input Table, Input Coordinate System, Output Feature Class, Output Coordinate System, Input Coordinate Format, X Field, Y Field, and Output Coordinate Format. The parameters were provided to the tool as shown in fig. 16.

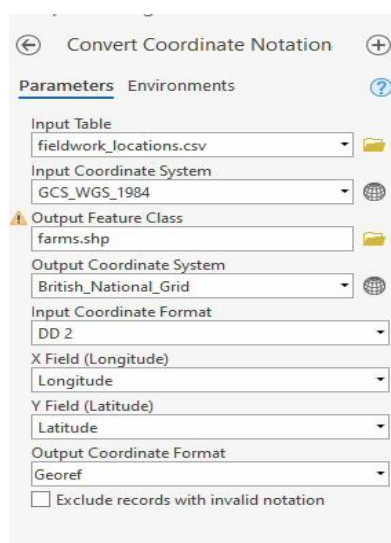


Fig. 16. Convert Coordinate Notation Tool usage.

For more information about the tool, visit <https://pro.arcgis.com/en/pro-app/latest/tool-reference/data-management/convert-coordinate-notation.htm>.

APPENDIX IV: Feature to Raster tool usage.

Feature to Raster tool from 'Conversion Toolbox' of 'Geoprocessing Tools' (ArcGIS Pro) was used multiple times to convert various shape files and geodatabase files into rasters as shape files had many useful attributes which could be individually visualised once they are converted to raster. For instance, the tool was used to convert UKSO pH and BulkDensity shape file to raster using Bulk Density field (BULKD_07) data to rasters as shown in fig. 17. Similarly, organic farms shape file was also converted to raster for visualisation.

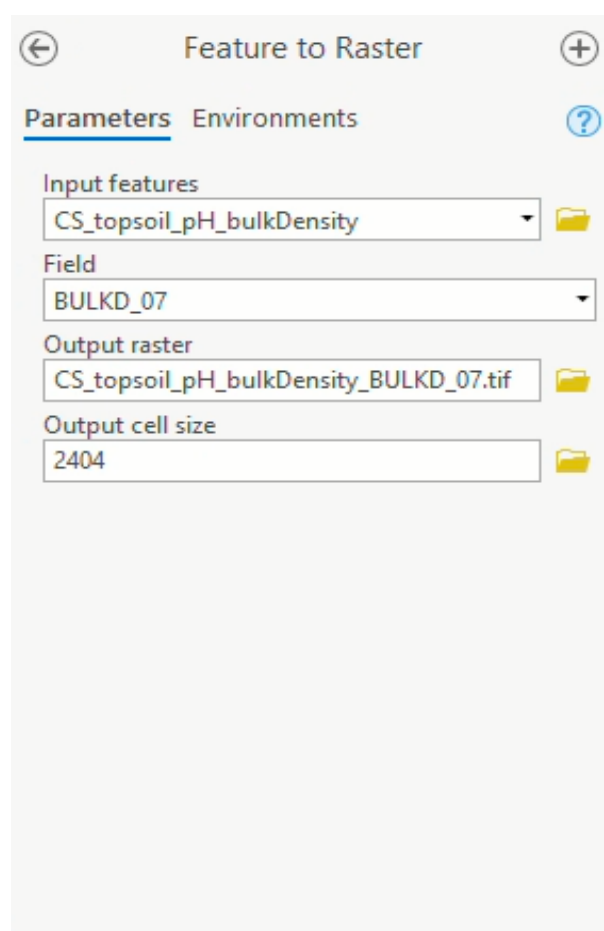


Fig. 17. Feature To Raster tool usage.

For more information about the tool, visit <https://pro.arcgis.com/en/pro-app/latest/tool-reference/conversion/feature-to-raster.htm>.

APPENDIX V: Using Symbology in ArcGIS Pro

Symbology is a unique tool available in ArcGIS Pro, it is available to use with rasters, geodatabases, and shape files as well. However, it was predominantly used with rasters during the research. To use symbology, right clicking on the layer in the ‘Contents’ panel is required first. Next, ‘Symbology’ option needs to be picked from the pop up list. With that, the symbology panel will appear on the right hand side of the ArcGIS Pro window as shown below. It offers many options to symbolise the output of a layer such as Stretch, Discrete, Classify, Unique Values, and Vector Field along with respective additional choices. For instance, with ‘Classify’ option, ‘Manual Interval’ method was chosen with 7 classes and colour scheme as shown in fig. 18.

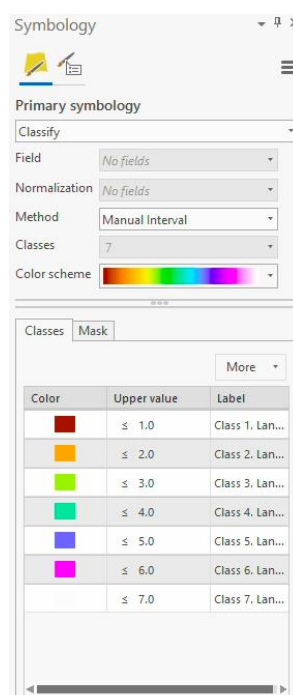


Fig. 18. Usage of Symbology tool.

For more information about the tool, visit <https://pro.arcgis.com/en/pro-app/latest/help/mapping/layer-properties/symbolization.htm>.

APPENDIX VI: Map Algebra calculation for agricultural ammonia

In ArcGIS Pro, map algebra can be applied on rasters by accessing ‘Raster Calculator’ from ‘Map Algebra’ toolset which is part of ‘Spatial Analyst’ toolbox under ‘Geoprocessing Tools’. Map Algebra is useful for applying arithmetic expressions / conditional statements pixel by pixel to one or more rasters which results in an output raster. For instance, Raster Calculator used in fig. 19 shows the application of conditional statement where if pixel value is less than or equal to 1, then pixel value from organic farm raster will be applied to the output raster. With this, all the organic farms where ammonia emissions were lower than or equal to 1 tonne were chosen for the output.

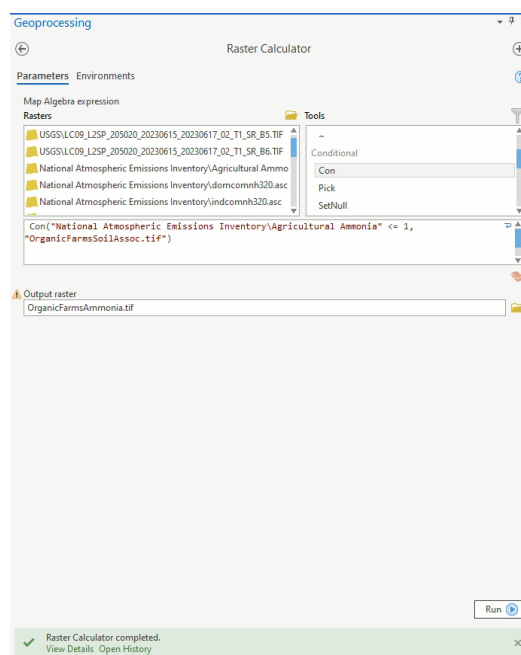


Fig. 19. Map Algebra with Raster Calculator.

For more information about Raster Calculator, visit <https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/raster-calculator.htm>.

APPENDIX VII: Using Spatial Join between feature classes

Spatial Join is a tool available in the ‘Overlay’ group of ‘Analysis tools’ from ‘Geoprocessing Tools’ within ArcGIS Pro. This tool allows to join two feature classes together based on their spatial relationship. It takes parameters such as Target Features, Join Features, Output Feature Class, Join Operation along with default settings for Output Fields, Match Options and Search Radius. For instance, fig. 20 shows organic farms being joined with UKSO nutrients dataset based on spatial coordinates of the two feature classes to create a joined output shape file.

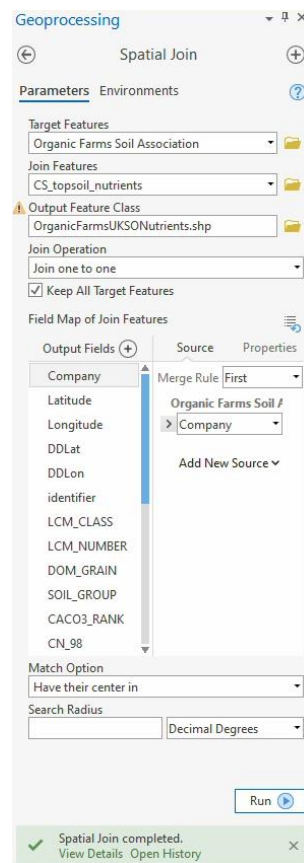


Fig. 20. Spatial Join tool usage.

For more information about Spatial Join tool, visit <https://pro.arcgis.com/en/pro-app/latest/tool-reference/analysis/spatial-join.htm>.

APPENDIX VIII: Python/ArcPy Scripts

1. Python script to process 162 rasters and convert them into shape file and CSV.

```

import arcpy
import csv
from pathlib import Path
arcpy.CheckOutExtension("Spatial")
from arcpy.sa import *
arcpy.env.workspace = "H:/Dissertation/Data/Download_fertilisers-
pesticides_2280498/Land-Cover-plus-Pesticides_5077694/"
rasters = arcpy.ListRasters("*","TIF")
#Iterate through rasters
for r in rasters:
    print("Processing raster: " + r)
    raster = "/" + r + "/Band_1"
    output = "/band1/" + r[:-4]
    arcpy.management.Delete(arcpy.env.workspace + output + ".shp")
    #Convert Raster to Point file
    arcpy.conversion.RasterToPoint(arcpy.env.workspace + raster, arcpy.env.workspace +
output + ".shp", "VALUE");
    filepath = arcpy.env.workspace + output + ".csv"
    if Path(filepath).exists():
        Path(filepath).unlink()
    print("Writing file: " + filepath)
    #Write CSV file
    with Path(filepath).open("w") as file:
        file.write("Easting, Northing, FID, Value\n")
        with arcpy.da.SearchCursor(arcpy.env.workspace + output + ".shp",
['SHAPE@XY', 'FID', 'grid_code']) as cursor:
            for row in cursor:
                file.write("{0}, {1}, {2}, {3}\n".format(row[0][0], row[0][1], row[1], row[2]))

```

2. Python script to read all CSVs and gather locations data

```

import arcpy
import csv
import os
from pathlib import Path
arcpy.CheckOutExtension("Spatial")
from arcpy.sa import *
arcpy.env.workspace = "H:/Dissertation/Data/Download_fertilisers-
pesticides_2280498/Land-Cover-plus-Pesticides_5077694/"
band1_dir = "/band1/"
files = os.listdir(arcpy.env.workspace + band1_dir)
loc_dict = {}
#Iterating through all CSVs
for f in files:
    if f[-3:] == "csv" and f[:9] != "locations":
        print("Reading locations from " + f)
        #Read CSV
        with Path(arcpy.env.workspace + band1_dir + f).open("r") as csvfile:
            reader = csv.DictReader(csvfile)
            #Process rows
            for row in reader:
                loc = row["Easting"].strip() + "," + row[" Northing"].strip()
                if not loc in loc_dict:
                    #Gather location
                    print("Gathering location : " + loc)
                    loc_dict[loc] = loc
print("Total locations found: " + str(len(loc_dict)))
print("Writing location file: locations.csv")
#Writing locations into CSV
with Path(arcpy.env.workspace + band1_dir + "locations.csv").open("w") as file:
    file.write("Easting,Northing\n")
    for str in loc_dict:
        file.write(str + "\n")
print("All locations gathered")

```

3. Python script to collect all pesticides data into single CSV.

```

import arcpy
import csv
import os
from pathlib import Path
arcpy.CheckOutExtension("Spatial")
arcpy.env.workspace = "H:/Dissertation/Data/Download_fertilisers-
pesticides_2280498/Land-Cover-plus-Pesticides_5077694/"
band1_dir = "/band1/"
output_dir = "/location_based_groups/"
files = os.listdir(arcpy.env.workspace + band1_dir)
loc_dict = {}
if Path(arcpy.env.workspace + band1_dir + output_dir + "all_pesticides.csv").exists():
    Path(arcpy.env.workspace + band1_dir + output_dir + "all_pesticides.csv").unlink()
#Opening final all_pesticides.csv file to write
with Path(arcpy.env.workspace + band1_dir + output_dir +
"all_pesticides.csv").open("w") as file:
    file.write("Easting,Northing,Pesticide,Amount\n")
#Iterating thru all CSVs
for f in files:
    if f[-3:] == "csv" and f[:9] != "locations":
        print("Writing pesticides data for file: " + f)
        with Path(arcpy.env.workspace + band1_dir + f).open("r") as csvfile:
            reader = csv.DictReader(csvfile)
            #Writing data
            for row in reader:
                file.write(row["Easting"].strip() + "," + row[" Northing"].strip() + "," + f[:4] + "," + row[" Value"].strip() + "\n")
        print("Pesticides for all locations are written for file: " + f)
print("All pesticides files processed.")

```

4. Python script to sort the single CSV and find most used pesticides per location.

```

import arcpy
import csv
import os
from pathlib import Path
arcpy.env.workspace = "H:/Dissertation/Data/Download_fertilisers-
pesticides_2280498/Land-Cover-plus-Pesticides_5077694/"
source_dir="/band1/location_based_groups/"
files = os.listdir(arcpy.env.workspace + source_dir)
loc_data = []
#Reading all_pesticides.csv file
print("Reading data for all pesticides")
with Path(arcpy.env.workspace + source_dir + "all_pesticides.csv").open("r") as file:
    reader = csv.DictReader(file)
    for row in reader:
        data =
(float(row["Easting"]),float(row["Northing"]),row["Pesticide"],float(row["Amount"]))
        loc_data.append(data)
print("Amount of data loaded: " + str(len(loc_data)))
#Sorting based on location
print("Sorting all pesticides data.")
sorted_list=sorted(loc_data, key=lambda x:(x[0], x[1]))
print("Amount of data sorted: " + str(len(sorted_list)))
current_easting = 0.0
current_northing = 0.0
print("Writing most used pesticides data")
if Path(arcpy.env.workspace + source_dir + "most_used_pesticides.csv").exists():
    Path(arcpy.env.workspace + source_dir + "most_used_pesticides.csv").unlink()
#Finding most used pesticides
with Path(arcpy.env.workspace + source_dir + "most_used_pesticides.csv").open("w") as
file:
    file.write("Easting,Northing,Pesticide,Amount\n")
    pesticides=[]
    for data in sorted_list:
        if float(current_easting) != float(data[0]) or float(current_northing) != float(data[1]):
            if len(pesticides) > 0:
                sorted_pesticides=sorted(pesticides, key=lambda x: (x[1]), reverse=True)
                count = 0
                #Writing most used pesticide for each location.
                for pesticide_data in sorted_pesticides:
                    file.write(str(current_easting) + "," + str(current_northing) + "," +
str(pesticide_data[0]) + "," + str(pesticide_data[1]) + "\n")
                    break
                pesticides=[]
            print("Working on location: " + str(current_easting) + "," + str(current_northing))
            current_easting = data[0]
            current_northing = data[1]
            pesticides.append((data[2],data[3]))
print("Data processed for all pesticides")

```

APPENDIX IX: CSV to Shape file using XY Table to Point tool

XY Table to Point tool is another tool used to convert tables to shape files. The tool is part of Feature toolset within Data Management Toolbox present in Geoprocessing Tools of ArcGIS Pro. The tool is straight forward to use as it accepts few parameters such as Input Table, Output Feature Class, X Field, Y Field, Z Field, and Coordinate System as shown in fig. 21.

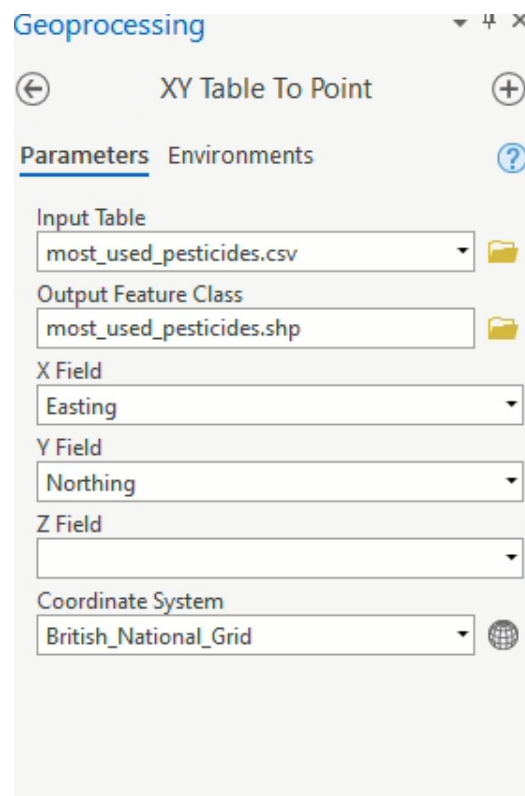


Fig. 21. XY Table To Point tool usage.

For more information about using XY Table to Point tool, visit <https://pro.arcgis.com/en/pro-app/latest/tool-reference/data-management/xy-table-to-point.htm>.