



# **ManureMap: A Spatial Manure Application Resource ArcGIS Toolbox® User’s Manual Version Beta**

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## PREFACE

### a Background

Manure can be an important contributor to agricultural nutrient budgets. When applied to crops at appropriate times and rates, it can provide several benefits over inorganic fertilizer, including improved soil quality, increased organic matter, decreased compaction, and increased water-holding capacity (McDonald et al. 2009). When applied at rates above crop needs, however, manure can pose a risk to water resources.

As the size and density of concentrated animal feeding operations has grown significantly over the past twenty-five years, so has the concern over the ability of the surrounding landscape to sustainably handle the byproducts of animal agriculture (Porter and James, 2020). A lack of information on the precise location of manure production and the assimilative capacity of proximal cropland has traditionally limited our assessment of manure contribution to the county scale, hindering our ability to identify localized areas with potentially high manure disposal pressure. The reliance on individual manure management plans, which often exist in a non-digital format and focus on a single operation at a time, poses additional challenges for understanding the cumulative impact of manure nutrients.

The increasing availability of high-resolution data has enabled many of these obstacles to be overcome. The ManureMap Toolbox provides a method to spatially characterize the application of manure nutrients from their point of production to proximal cropland in agricultural landscapes based on crop nutrient needs. The tools are designed to utilize field boundaries and land use information derived from the Agricultural Conservation Planning Framework (ACPF) (Tomer et. al. 2013).

### b Modeling Approach and Timeframe

Several different approaches are provided to define the rate at which manure is applied to nearby cropland, requiring careful consideration by the user of the desired end goal. The three provided approaches are listed below and are dependent on crop Nitrogen (N) removal, crop Phosphorus (P) removal, or crop N fertilizer recommendations. Note that the term “field nutrient need” is referred to throughout the remainder of this manual. This need is defined by the approach that the user selects, and for each field can represent the amount of N removed, P removed, or N fertilizer recommended.

1. N fertilizer application rate. Manure is applied to meet the N fertilizer recommendation of crops.
2. N removal application rate. Manure is applied to meet the N removal of crops.
3. P removal application rate. Manure is applied to meet the P removal of crops.

In addition to the approaches defined above, the user will select the timeframe for which to model manure application. The two available timeframe options include:

1. Across a Rotation. Manure is applied to meet field nutrient needs **over the course of a crop rotation**. This is defined by an average annual nutrient need for each field.
2. Single Year. Manure is applied to meet field nutrient needs **for a single year at a time for several years in succession**. Model results from several years are then summarized across a crop rotation. As described in detail in later sections of this manual, the primary benefit of this approach is that it enables residual manure N (second year availability of manure N) to be tracked and appropriately credited year to year.

### c Geographic Scope

While the ACPF was developed to run at the scale of the Hydrologic Unit Code (HUC) 12 watershed, characterizing manure application at this scale can result in significant bias due to the movement of manure across watershed boundaries. It is therefore recommended that the ManureMap tools be run at a regional scale, such as a large watershed or statewide.

### d Structure and Required Data Inputs

***All data should be stored in an ArcGIS file geodatabase, and all output files should be written back to the original fgdb.*** In contrast to the ACPF toolbox, there are no required naming conventions for input or output files. However, default filenames will automatically be populated as the user runs the tools.

The ManureMap toolbox requires two primary data inputs to be provided by the user, as described below.

1. **Field boundaries and land use information in the same data structure as the ACPF.** Any user-generated field boundary polygons can serve as a starting point for this without any required attribution.

To obtain the required data structure for use with the ManureMap toolbox, the “Update Edited Field Boundaries” tool within the ACPF toolbox must be run. Outputs will include ACPF-structured field boundaries, a crop history (“CH”) table, and a six-year land use (“LU6”) table. The “Update Edited Field Boundaries” tool can be run at scales larger than the HUC-12 watershed, such as regional or statewide. More details on running this tool can be found in the user manual that is provided with a download of the ACPF toolbox. In brief, the tool requires that user-provided field boundaries exist within an ArcGIS file geodatabase along with a minimum of 6 years of the NASS Cropland Data Layer (CDL). The extent of the NASS CDL rasters must cover all field boundaries provided.

The ACPF toolbox can be downloaded from [www.acpf4watersheds.org](http://www.acpf4watersheds.org). Field boundary and land use data can also be obtained from this website, although this data will be provided at a HUC-12 watershed scale. To enable processing at a regional scale, field boundaries and land use information would need to be merged from neighboring HUC-12 watersheds. This process can be tedious and prone to errors resulting in duplicate fields and invalid topology.

An alternative option is to obtain regional or statewide datasets of ACPF field boundaries and land use information from the USDA Ag Data Commons. Several statewide datasets (including Minnesota, Iowa, Illinois, Nebraska, and Wisconsin) have been published on this website and can be accessed through the search term “ACPF” here: <https://catalog.data.gov/dataset/>.

The user may also wish to contact the ACPF National HUB at [acpfsupport@iastate.edu](mailto:acpfsupport@iastate.edu) to collaborate and receive support for obtaining field boundary and land use datasets at scales larger than the HUC-12 watershed.

2. **Point-level dataset of animal feeding operations with crop-available manure N and P.**

It is expected that the user provides not only point locations of animal feeding operations, but also crop available manure nutrients (N and P) from each location. A minimum of three attribute fields (optionally 4) should exist within the provided point layer. There are no required naming conventions for the following field names, but they should represent:

1. A unique identifier for each animal feeding operation (required).
2. Year One crop-available manure N (lbs) (required).
3. Year Two crop-available manure N (lbs) (optional).
4. Crop-available manure P (lbs of elemental P, not P205) (required).

Due to the complexities associated with the timing of manure nutrient availability, the user may choose to distinguish between manure N that is crop available in the same year that it is applied (year one manure N) and that which will become available in the year following application (year two manure N). As described in later sections of this manual, the primary advantage of the “Apply Manure – Single Year” tool is that it allows for year two manure N to be tracked and appropriately credited year to year. When year two manure N is not known, the user may choose to run the “Apply Manure – Across a Rotation” tool.

The ManureMap toolbox does not currently provide a method for the estimation of crop available manure nutrients from each animal feeding operation. This is a complex process that is compounded by the fact that data availability on feedlot location and type and number of animals housed varies significantly from state to state. In areas where data is readily available, assumptions must be made regarding manure recoverability and losses during storage, handling, and application. While book values are often relied upon to make these assumptions, these can vary significantly from actual manure nutrient content data that is collected by labs across the country.

## e Current Limitations

The intent of the ManureMap toolbox is to model the application of ***crop available manure nutrients*** to proximal agricultural land. Significant losses (of primarily N) occur between the point of manure production (excretion from the animal) and the point of land application. While these nutrients are often considered unavailable to crops and therefore largely ignored from an agronomic perspective, these nutrients have the potential to pose an environmental risk to local air and water quality.

Modeling outputs are meant to ***characterize*** the assimilative capacity of cropland to uptake manure nutrients based on the spatial proximity of agricultural land to the point at which manure production takes place. There is no guarantee that individual fields modeled to receive manure will align with fields actually receiving manure, and these results should not be used in place of nutrient and manure management plans.

Manure application occurs based spatial proximity alone. While the modeling process is described in more detail below, the concept is simple in that manure is applied to the most proximal fields with a nutrient need from the point at which it is produced. Advances in manure handling techniques, including the use of digesters and liquid/solid separation, continue to allow for manure to travel further distances. This is particularly true for solid manure associated with poultry operations. Currently there is no method to account for the variability in hauling distance for different animal types.

## f Using Data Outputs

Numerous attribute fields are created while running these tools, and a misinterpretation of results can create bias regarding the role of manure nutrients. To simplify and streamline how results are mapped and reported, guidance on the interpretation of attribute fields is provided at the end of this user manual (Section x).

## g Crops Included for Modeling

Twenty-two crops can be currently modeled in the ManureMap Toolbox. These crops are identified within each tool by the NASS CDL value that is contained within the “maj” attribute field of the ACPF crop history (“CH”) table. The “maj” attribute field lists the dominant NASS CDL value within each field for each year that the NASS CDL was provided. The “maj” field provides the method by which crops (and years) are selected within the toolbox for modeling purposes.

Current Crops Included for Modeling in Manure Application Toolbox		
Crop Name	NASS CDL Value	ACPF Rotation Value
Alfalfa	36	P
Barley	21	G
Canola	31	O
Corn	1	C
Cotton	2	N
Dry Beans	42	M
Durum Wheat	22	W
Millet	29	G
Oats	28	G
Other Hay / Non Alfalfa	37	P
Peanuts	10	A
Peas	53	M
Potatoes	43	V
Rice	3	J
Rye	27	G
Sorghum	4	H
Soybeans	5	B
Spring Wheat	23	W
Sugarbeets	41	E
Sunflower	6	O
Tobacco	11	R
Winter Wheat	24	W

## h Lookup Tables

Three lookup tables are provided with a download of the ManureMap toolbox and can be found in the ‘Lookup Tables’ folder. These tables include:

1. **Nutrient Removal Lookup Table:** Provides default values for lbs of N and P removed per unit yield for each of the 22 crops identified above. Nutrient removal rates were obtained from the USDA Crop Nutrient Tool.
2. **Nitrogen Fertilizer Lookup Table:** Provides default values for N fertilizer recommendations (in lbs per acre) for each of the 22 crops listed above.

3. **ACPF NASS Land Use Lookup Table:** Provides NASS CDL values and assigned ACPF rotation values.

**IMPORTANT:** Default values provided in the lookup tables are not meant to be uniformly applied for all regions of the country. While nutrient removal rates are inherent properties of each crop, these values generally stay consistent region to region. Nitrogen fertilizer recommendations, however, vary significantly throughout the country and even within states. The price of fertilizer, climate, soil type, and irrigation practices (among others) play a significant role in determining the most applicable N fertilizer rate for use in modeling purposes. It is therefore highly recommended that the user carefully examines the values in the provided lookup tables and manually edit the values to suit the agricultural system in which they are working. More detail on how to edit these tables is described within each tool description below.

Nutrient Removal Lookup Table						
CROP	NASS VALUE	ACPF ROTVAL	Nutrient Removal (lbs per unit yield)		Unit	USDA Crop Nutrient Tool Category
			N	P		
Alfalfa	36	P	50.3935	4.7217	Ton	Alfalfa, for hay
Barley	21	G	0.8938	0.1777	Bushel	Barley-6 row, for grain (exc. Pacific Coast)
Canola	31	O	0.035415	0.005646	Lb	Canola, for seed
Corn	1	C	0.7929	0.1514	Bushel	Corn-Field, for grain (shelled, yellow dent, grade # 1)
Cotton	2	N	0.0304	0.0038	Lb	Cotton, for seed with lint or seed cotton
Dry Beans	42	M	0.037425	0.004784	Lb	Bean, for seed (dry)
Durum Wheat	22	W	1.2866	0.224	Bushel	Wheat-Durum, for grain
Millet	29	G	1.0497	0.1693	Bushel	Millet-Pearl, for grain
Oats	28	G	0.5984	0.1092	Bushel	Oat, for grain (not including Pacific Coast)
Other Hay/Non Alfalfa	37	P	27.8796	2.9142	Ton	Bromegrass, for hay
Peanuts	10	A	0.0396	0.0033	Lb	Peanut, for fruit (pod with seeds)
Peas	53	M	0.0373	0.0044	Lb	Pea-Field, for seed (dry)
Potatoes	43	V	0.3667	0.0563	CWT	Potato-Irish, for tuber
Rice	3	J	0.012296	0.02538	Lb	Rice-Rough, for grain
Rye	27	G	1.0557	0.1873	Bushel	Rye, for grain
Sorghum	4	H	0.9288	0.1655	Bushel	Sorghum, for grain
Soybeans	5	B	3.5419	0.3628	Bushel	Soybean, for grain
Spring Wheat	23	W	1.4366	0.2309	Bushel	Wheat-Bread-Hard Red Spring, for grain
Sugarbeets	41	E	4.3595	0.9013	Ton	Sugarbeet, root without crown
Sunflower	6	O	0.027729	0.005803	Lb	Sunflower, for seed (with hull, oil type)
Tobacco	11	R	0.03	0.00234	Lb	Tobacco-Air cured, Burley type
Winter Wheat	24	W	1.2205	.2305	Bushel	Wheat – Bread – Hard Red Winter, for grain
SOURCE: USDA Crop Nutrient Tool: <a href="https://plants.sc.egov.usda.gov/home/tools">https://plants.sc.egov.usda.gov/home/tools</a>						

Nitrogen Fertilizer Lookup Table					
CROP	NASS VALUE	PREV NASS	ACPF ROTVAL	N Fertilizer (lbs /acre)	SOURCE
Alfalfa	36	0	P	0	---
Barley	21	0	G	67	NASS 2019 Pre-Defined QUERY, national avg.
Canola	31	0	O	80	NDSU Fertilizing Canola and Mustard, assumes 120 lb/acre maximum application rate and a 40 lb/acre credit.
Corn	1	0	C	195	

	1	5	C	150	Average .10 MRTN rates for 'corn following corn' and 'corn
<b>Cotton</b>	2	0	N	95	NASS 2021 Pre-Defined QUERY, national avg.
<b>Dry Beans</b>	42	0	M	71	NASS 2022 Pre-Defined QUERY, national avg. (snap beans)
<b>Durum Wheat</b>	22	0	W	82	NASS 2022 Pre-Defined QUERY, national avg.
<b>Millet</b>	29	0	G	20	CSU Fertilizing Spring-Seeded Small Grains, low soil NO <sub>3</sub> -N
<b>Oats</b>	28	0	G	51	NASS 2015 Pre-Defined QUERY, national avg.
<b>Other Hay/Non Alfalfa</b>	37	0	P	60	Average N recommendation for hayland from several midwestern/western states
<b>Peanuts</b>	0	0	A	32	NASS 2018 Pre-Defined QUERY, national avg.
<b>Peas</b>	53	0	M	50	NASS 2022 Pre-Defined QUERY, national avg. (green peas)
<b>Potatoes</b>	43	0	V	178	NASS 2022 Pre-Defined QUERY, national avg.
<b>Rice</b>	3	0	J	180	NASS 2021 Pre-Defined QUERY, national avg.
<b>Rye</b>	27	0	G	60	NDSU Fertilizing Winter Rye, assuming medium productivity and a 40 lb/acre credit.
<b>Sorghum</b>	4	0	H	77	NASS 2019 Pre-Defined QUERY, national avg.
<b>Soybeans</b>	5	0	B	17	NASS 2020 Pre-Defined QUERY, national avg.
<b>Spring Wheat</b>	23	0	W	80	NASS 2022 Pre-Defined QUERY, national avg.
<b>Sugarbeets</b>	41	0	E	55	MN Extension Fertilizing Sugarbeet, lower range of N guideline for Southern Minnesota Beet Sugar Cooperative, assumes 1/2 of recommended N is provided by soil NO <sub>3</sub> -N.
<b>Sunflower</b>	6	0	O	150	North Dakota Sunflower N Calculator, Eastern North Dakota, Oil-seed Conventional Till, no known soil NO <sub>3</sub> -N.
<b>Tobacco</b>	11	0	R	65	NC State Extension Tobacco Growers Information, avg. topsoil depth.
<b>Winter Wheat</b>	24	0	W	72	NASS 2022 Pre-Defined QUERY

**SOURCES:**

NASS Pre-Defined Queries: [https://www.nass.usda.gov/Data\\_and\\_Statistics/Pre-Defined\\_Queries/index.php](https://www.nass.usda.gov/Data_and_Statistics/Pre-Defined_Queries/index.php)

NDSU Fertilizing Canola and Mustard: <https://www.ndsu.edu/agriculture/extension/publications/fertilizing-canola-and-mustard>

Corn MRTN Calculator: <https://www.cornnratecalc.org/>

CSU Fertilizing Spring-Seeded Small Grains: <https://erams.com/agnutrient/co-bmp-library/fertilizing-spring-seeded-small-grains-2/>

NDSU Fertilizing Winter Rye: <https://www.ndsu.edu/agriculture/extension/publications/fertilizing-winter-rye>

MN Extension Fertilizing Sugarbeet: <https://extension.umn.edu/crop-specific-needs/sugarbeet-fertilizer-guidelines>

North Dakota Sunflower N Calculator: <https://www.ndsu.edu/pubweb/soils/sunflower/>

NC State Extension Tobacco Growers Information: <https://tobacco.ces.ncsu.edu/tobacco-fertility-nutrients/>

## Utility: Summarize Agricultural Land Use

Required Inputs	Outputs
Input Layer: Field Boundaries (must contain "FBndID" and "Acres" field)	Agricultural Land Use Summary Table (AgLUSummary)
Input Layer: ACPF Crop History table (must contain "FBndID")	
Year(s) to Summarize Land Use (user selection)	
Input Table: ACPF NASS Land Use Lookup Table	

Although considered a utility, it is recommended that this tool be run prior to any others to gain an understanding of the crops grown in the region of interest. This information should guide the user on which crops to select for manure application and to focus attention for determining appropriate lookup values for nutrient removal and/or N fertilizer recommendations.

The output table provides a summary of ACPF agricultural land use, defined by an isAG value of '1' (cropland) or '2' (pasture), within the user provided field boundaries. Importantly, the tool assumes that the dominant land cover within each field occupies the entire acreage of the field. Therefore, acreage estimates derived from this tool will differ from estimates derived from raw NASS CDL pixels. In general, acreages associated with less prevalent land use classes will decrease as pixels are aggregated within each field.

The user must specify which year(s) to summarize by selecting one or more "maj" field(s) from the ACPF crop history table. The "maj" attribute field lists the dominant NASS CDL land cover within each field. The name of each "maj" attribute field is followed by a 2-digit ID corresponding to the year it represents (i.e. "maj17" = majority NASS CDL value within each field in 2017).

All NASS CDL values that exist within the area of interest and that are considered agricultural land use are reported in the output table along with its common name (example: NASS CDL value of 1, 'Corn') and the associated acreage (Acres'xx') of that land cover for each year specified. This acreage represents the sum of all field acreage with the dominant NASS CDL value in each year. Two additional summary fields are added, representing the average annual acreage of each land cover across all years as well as its percentage of total agricultural acreage.

**IMPORTANT:** The ACPF NASS Land Use Lookup Table is provided with a download of the ManureMap Toolbox and can be found in the 'Lookup Tables' folder.

### Output Agricultural Land Use Summary Table

ATTRIBUTES	DESCRIPTION
<b>Cdlcode</b>	NASS CDL value associated with each crop.
<b>Crop</b>	Class Name of NASS CDL value.
<b>Acres'xx'</b>	Sum of field acreage by dominant NASS CDL value. 'xx' equals the last 2 digits of the processing year.
<b>Avg'x'Yr</b>	Average annual field acreage by NASS CDL value. Calculated by summing the field acreage by crop type for all years then dividing by the number of years. 'x' equals the number of years summarized.
<b>PctTot'x'Yr</b>	Percent of total field acreage that each NASS CDL value represents. Calculated by dividing the average annual field acreage by the total annual average cropland acreage.

## DEFINING FIELD NUTRIENT NEED

### 1a. Create Six Year Yield Table

Required Inputs	Outputs
Input Layer: Field Boundaries	Output Yield Table: YieldTable'xxxx'_yyyy', where 'xxxx' equals the first year and 'yyyy' equals the last year of the six-year timeframe.
Input Layer: Tiger County Boundaries	
Input Table: Quick Stats Crop Table (qs.crops)	
First Year of Six Year Rotation	
Last Year of Six Year Rotation	

Yield information is required to estimate the amount of N and P removed from each agricultural field during crop harvest, a required input to model manure application to fields on a nutrient removal basis.

Rarely is yield information publicly available at a sub-county scale, and county-level yield information derived from NASS surveys is often considered the most reliable source of information. This tool calculates a six-year average county yield from NASS surveys for each of the 22 crops included in the toolbox. Only counties that contain a field centroid from the user-provided field boundaries will be included. In follow-on tools that calculate nutrient removal by field, an average county yield for each crop will be assigned using the county in which the center of the field is located.

County-level yield averages are not always available due to the nature of NASS surveys, for which data collection varies by geographic region. A given county may have six years of NASS yield information on 'corn for grain', for example, while a neighboring county has none. Reasons for a lack of published yield data include limited crop production, exclusion to maintain confidentiality of individual identifying information, or areas not included in the NASS county estimating program.

**IMPORTANT:** The user must provide a US TIGER county shapefile (US Census Bureau) or a feature class that contains a "GEOID" attribute field in the same format. A US TIGER county shapefile can be downloaded from the following website: <https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html>.

**IMPORTANT:** A quick stats crop table (qs.crops\_date.txt.gz) can be downloaded from the following NASS website which is updated daily: <https://www.nass.usda.gov/datasets/>.

Please note that the quick stats crop table file is very large. It must first be unzipped, following which the .txt table can be opened directly within ArcGIS software. ***The .txt file must then be copied into a file geodatabase table to be used by ArcGIS geoprocessing tools. Steps for copying the .txt file into a file geodatabase include:***

1. From the catalog pane within ArcGIS, navigate to the location of the unzipped "qs.crops\_date.txt.gz" file. The qs.crops\_date.txt file can be added directly to the table of contents.
2. Create a new, empty file geodatabase that will contain a copy of the .txt file. To do this from within the ArcGIS catalog pane, navigate to the location where you would like to store the new file geodatabase. Due to the size of the .txt file, it is recommended **NOT** to use the same file

geodatabase containing the layers for your study area. Right-click and select New --> File Geodatabase. Specify a name for the new fgdb, such as "QuickStats.gdb".

- Right click on the .txt file from within the ArcGIS table of contents and select Data --> Export Table. Navigate to the empty file geodatabase that was just created and provide a name for the copied table, such as "qs\_crops\_'date'", where 'date' indicates the date of download. Click OK. Once exported, the .txt file should now exist within the fgdb as a file geodatabase table.

The following table lists each of the 22 crops, the associated "SHORT\_DESC" from NASS surveys that is used to obtain crop yield information, and the unit for which yield data is reported on a per acre basis.

Crop Name	SHORT_DESC	Unit
Alfalfa	HAY, ALFALFA - YIELD, MEASURED IN TONS / ACRE	Tons
Barley	BARLEY - YIELD, MEASURED IN BU / ACRE	Bushel
Canola	CANOLA - YIELD, MEASURED IN LB / ACRE	Lbs
Corn	CORN, GRAIN - YIELD, MEASURED IN BU / ACRE	Bushel
	CORN, SILAGE - YIELD, MEASURED IN TONS / ACRE	Tons
Cotton	COTTON, UPLAND - YIELD, MEASURED IN LB / ACRE	Lbs
Dry Beans	BEANS, DRY EDIBLE, INCL CHICKPEAS - YIELD, MEASURED IN LB / ACRE	Lbs
Durum Wheat	WHEAT, SPRING, DURUM - YIELD, MEASURED IN BU / ACRE	Bushel
Millet	MILLET, PROSO - YIELD, MEASURED IN BU / ACRE	Bushel
Oats	OATS - YIELD, MEASURED IN BU / ACRE	Bushel
Other Hay / Non Alfalfa	HAY, (EXCL ALFALFA) - YIELD, MEASURED IN TONS / ACRE	Tons
Peanuts	PEANUTS - YIELD, MEASURED IN LB / ACRE	Lbs
Peas	PEAS, DRY EDIBLE - YIELD, MEASURED IN LB / ACRE	Lbs
Potatoes	POTATOES - YIELD, MEASURED IN CWT / ACRE	CWT
Rice	RICE - YIELD, MEASURED IN LB / ACRE	Lbs
Rye	RYE - YIELD, MEASURED IN BU / ACRE	Bushel
Sorghum	SORGHUM, GRAIN - YIELD, MEASURED IN BU / ACRE	Bushel
Soybeans	SOYBEANS - YIELD, MEASURED IN BU / ACRE	Bushel
Spring Wheat	WHEAT, SPRING, (EXCL DURUM) - YIELD, MEASURED IN BU / ACRE	Bushel
Sugarbeets	SUGARBEETS - YIELD, MEASURED IN TONS / ACRE	Tons
Sunflower	SUNFLOWER, OIL TYPE - YIELD, MEASURED IN LB / ACRE	Lbs
Tobacco	TOBACCO, AIR-CURED LIGHT BURLEY (TYPE 31) - YIELD, MEASURED IN LB / ACRE	Lbs
Winter Wheat	WHEAT, WINTER - YIELD, MEASURED IN BU / ACRE	Bushel

The input quick stats table is filtered to select only those records that have "SURVEY" yield information at a "STATE", "COUNTY", or "NATIONAL" scale, a year within the range specified by the user, a "REFERENCE\_PERIOD\_DESC" of "YEAR", and a "SHORT\_DESC" that is in the table above. For each crop, the quick stats table is queried to determine if at least one year out of the six contains county-level yield information for each county in the study area. If this criterion is met, an average yield is calculated for that county using all years in which information is provided at this scale. For example, if county yield information is provided for 2 out of the 6 years, a six-year average yield will be calculated by averaging those 2 years.

If no county yield information exists for a given crop in a given county, the quick stats table is queried to determine if at least one year out of the six contains state-level data. If this criterion is met, a six-year average yield is calculated using state-level yield data using the same process as described above. If no data exists at the county or state level, the quick stats table is queried to determine if at least one year out of the six contains national-level data. If no data exists for a crop at any scale for a given county, the tool will provide a message (accessible through the messages window in ArcPro geoprocessing) and all yield information for that crop and county will be given a value of zero.

**IMPORTANT:** A user may wish to provide their own yield values for crops rather than rely on NASS surveys. To do so, a user would manually edit the yield values in the output yield table for each crop. Using oats as an example, the user would manually edit the values in the “OatsYld” attribute field to represent the desired yield value for each county. At this point in time, it is not possible to allow for sub-county variability in crop yields.

**IMPORTANT:** It is extremely important to verify that yield data is reported in the same units at which nutrient removal rates are provided in the nutrient removal lookup table. For example, since oat yields are reported by NASS surveys in *bushels/acre*, the nutrient removal rates provided in the lookup table should reflect *bushels* as the unit for nutrient removal. By default, all crop nutrient removal units have been converted to match the units provided in the yield data that is generated using the “Calculate Six Year Average Yield Table” tool.

**IMPORTANT:** Note that average county yields for both corn for grain (yield reported in bushels/acre) and corn for silage (yield reported in tons/acre) are obtained as part of this tool. ***Importantly, if corn for silage is selected in follow on tools to represent the yield for all fields planted to corn, the user must manually edit the Nutrient Removal lookup table to reflect nutrient removal per unit ton of corn silage.*** Failure to change the lookup table will result in large errors in output data values.

**Output Six Year Yield Table**

ATTRIBUTES	DESCRIPTION
GEOID	Unique Identifier for each county using the TIGER county shapefile.
'x'Yld	Six-year average yield value.
'x'Scale	The scale at which data is reported (“County”, “State”, or “National”).
'x'Cnt	The number of years (out of six) for which yield data was provided at that scale.
'x'Unit	The unit for which yield data is reported on a per acre basis.
'x' equals a prefix for each crop. For each crop, four fields will be provided in the output yield table ('Yld', 'Scale', 'Cnt', and 'Unit'). Prefixes are defined by:	
Alfalfa: 'Alfalfa'	Millet: 'Millet'
Barley: 'Barley'	Oats: 'Oat'
Canola: 'Canola'	Other Hay / Non Alfalfa: 'OthHay'
Corn for Grain: 'CornGrn'	Peanuts: 'Peanut'
Corn for Silage: 'CornSil'	Potatoes: 'Potato'
Cotton: 'Cotton'	Rice: 'Rice'
Dry Beans: 'DryBean'	Rye: 'Rye'
Sorghum: 'Sorghum'	Soybean: 'Soybean'
Spring Wheat: 'SprWht'	Sugarbeet: 'SBeet'
Sunflower: 'Sunflow'	Tobacco: 'Tobacco'
Winter Wheat: 'WinWht'	

## 1b. Field Nutrient Removal: Nitrogen and Phosphorus

Required Inputs	Outputs
Input Layer: Field boundaries (must contain "FBndID" and "Acres" field)	Output Nutrient Removal table: 'NutrientRemoval_XXXX_YYYY', where 'XXXX' equals the first year modeled and 'YYYY' equals the last year modeled.
Input Table: ACPF Crop History table (must contain "FBndID")	
Input Layer: TIGER county boundaries (must contain "GEOID")	
Year(s) to Model Nutrient Removal (user selection)	
Select One or More Crops to Model (user selection)	
Input Table: Nutrient Removal Lookup table	
Input Table: Yield Table	
Input Field: Attribute field containing county yield values for each crop	

This tool estimates lbs of nutrients removed (N and P) during crop harvest from each field in the user-provided field boundaries. The user selects which crops (out of the 22 available for modeling) for which they would like to calculate nutrient removal and the year(s) to include. The user-provided Nutrient Removal lookup table must contain nutrient removal rates (lbs removed per unit yield) and the user-provided six-year average yield table (output from "Create Six Year Average Yield Table") must contain average county yields for each crop selected.

**IMPORTANT:** Regardless of the crops included in the nutrient removal lookup table, nutrient removal will only be calculated for those crops selected within the tool interface, and N and P removal will equal zero for all crops not selected. For follow-on tools that model manure application using a nutrient removal approach, only fields with a value > 0 will be eligible to receive manure each year. If a user would like to model manure application to just corn using a nutrient removal rate, for example, only 'corn' should be selected within the user interface.

**IMPORTANT:** Within the nutrient removal lookup table, the NASS CDL value is used to identify the nutrient removal associated with each crop. For example, if 'corn' is selected by the user, a corresponding row in the nutrient removal lookup table must contain a '1' value in the 'NASSVALUE' field, along with values for "NRemoval", "PRemoval", and "UnitYield".

For each crop specified by the user, a corresponding attribute field must also be selected from the provided yield table. If corn is selected, for example, the user must identify the attribute field from the six-year yield table that contains county yield averages for corn.

**IMPORTANT:** It is extremely important to ensure that yield data is reported in the same units at which nutrient removal rates are provided in the nutrient removal lookup table. By default, all crop nutrient removal units have been converted to match the units provided in the output table that is generated using the "Create Six Year Yield Table" tool. The exception to this is corn, for which county yield averages are reported for both corn for grain (yield reported in bushels/acre) and corn for silage (yield reported in tons/acre). By default, the nutrient removal lookup table contains values *per unit bushel* of corn for grain. ***If corn for silage yield is selected from the yield table, the user must manually edit the nutrient***

**removal lookup table to reflect nutrient removal values per unit ton of corn silage.** Failure to change the lookup table may result in large errors in output data values.

By default, the NASS CDL crops of sweet corn and triticale will be treated the same as corn and rye, respectively. Additionally, NASS CDL double crop categories (example: double crop winter wheat/soybeans) will be modeled for each crop separately then summed to represent the nutrient removal for that year. Given that 22 crops are currently included for potential analysis, not all double crop systems will be represented by both crops explicitly. An example is a field growing “double crop lettuce/durum wheat”, for which lettuce is not currently included in the ManureMap toolbox. In this example, nutrient removal will be calculated only for the durum wheat portion of the rotation, assuming that durum wheat is selected by the user.

For each field and year specified, the tool will calculate the lbs of N and P removed using the following equations:

- $N \text{ removal (in lbs)} = \text{field acres} * \text{lbs of N removed per unit yield of crop grown} * 6\text{-year average yield of crop grown.}$
- $P \text{ removal (in lbs)} = \text{field acres} * \text{lbs of P removed per unit yield of crop grown} * 6\text{-year average yield of crop grown.}$

**Output Nutrient Removal Table**

<b>ATTRIBUTES</b>	<b>DESCRIPTION</b>
<b>FBndID</b>	Field boundary ID. Can be used to join to field boundary feature class.
<b>Nrem'xx'</b>	Lbs of N removed by each field for each year specified, where 'xx' equals the last two digits of the year ("nrem17" equals N removed in 2017). A "Nrem" field will be added for each year specified.
<b>Prem'xx'</b>	Lbs of P removed by each field for each year specified, where 'xx' equals the last two digits of the year ("prem17" equals P removed in 2017). A "Prem" field will be added for each year specified.
<b>Nrem'x'Yr</b>	Total lbs of N removed by each field across all years specified.
<b>Prem'x'Yr</b>	Total lbs of P removed by each field across all years specified.
<b>Nrem'x'YrAnn</b>	Average annual lbs of N removed by each field. Calculated by summing the N removed across all years specified then dividing by the number of years.
<b>Prem'x'YrAnn</b>	Average annual lbs of P removed by each field. Calculated by summing the P removed across all years specified then dividing by the number of years.

## 2. Field Nitrogen Fertilizer

Required Inputs	Outputs
Input Layer: Field Boundaries (must contain "FBndID" and "Acres" field)	Output Nitrogen Fertilizer table: 'NitrogenFertilizer_XXXX_YYYY', where 'XXXX' = equals the first year modeled and 'YYYY' equals the last year modeled.
Input Table: ACPF Crop History table (must contain "FBndID")	
Year(s) to Model Nitrogen Fertilizer (user selection)	
Select One or More Crops to Model (user selection)	
Input Table: Nitrogen Fertilizer Lookup table	

This tool estimates lbs of N fertilizer recommended for each field in the user-provided field boundaries. The user selects which crops (out of the 22 available for modeling) for which they would like to calculate N fertilizer recommendations and the year(s) they would like to include. The user-provided N fertilizer lookup table must contain N fertilizer recommendations for each crop selected.

**IMPORTANT:** Regardless of the crops included in the N fertilizer lookup table, fertilizer recommendations will only be calculated for those crops selected within the tool interface, and N fertilizer will equal zero for all crops not selected. For follow-on tools that model manure application using a N fertilizer approach, only those fields with a value > 0 will be eligible to receive manure each year. If a user would like to model manure application to just corn using a N fertilizer rate, for example, only 'corn' should be selected within the user interface.

**IMPORTANT:** Within the N fertilizer lookup table, the NASS CDL value is used to identify the N fertilizer recommendation associated with each crop. For example, if 'corn' is selected by the user, a corresponding row in the N fertilizer lookup table must contain a '1' value in the 'NASSVALUE' field, along with values for "PREVNASS" and "NFertLbsAc".

The "PREVNASS" attribute field allows the user to model different application rates to the same crop based on the crop grown the previous year. A "PREVNASS" value of '0' indicates no reliance on the crop grown the previous year and will result in the same N fertilizer recommendation regardless of the previous crop grown. **There must be at least one row** in the N fertilizer lookup table with a value of "0" for "PREVNASS", which will represent the fertilizer rate for all previous crops not specifically identified through the "PREVNASS" column.

**IMPORTANT:** If the user would like to vary the N fertilizer rate dependent on the previous crop grown, a row must be added to the N fertilizer lookup table and values manually entered for "NASSVALUE", "PREVNASS", and "NFertLbsAc". The "NASSVALUE" should contain the NASS CDL value for the crop being fertilized, the "PREVNASS" field should contain the NASS CDL value for the crop grown the year prior, and the "NFertLbsAc" should indicate the recommended N fertilizer application rate in lbs per acre.

The default N fertilizer lookup table contains two rows for corn, for example, one listing the fertilizer rate for corn following soybean (PREVNASS value of '5') and the other row listing the fertilizer rate for corn following all other crops (PREVNASS value of '0').

**IMPORTANT:** There will be no previous crop identified during the first processing year. If “maj17” is selected as the first year, for example, all crops will be given the N fertilizer rate for which no previous crop has been specified (i.e. a “PREVNASS” value of “0”). The user may choose to run the tool for a “warmup” year if the goal is to summarize manure application over a specific time-period while ensuring that previous-crop dependent rates are used for each year. For example, if a user would like to summarize manure application between 2017 and 2022, N fertilizer recommendations can be calculated from 2016 to 2022 (using 2016 as a warmup year) with the intention that manure application will be summarized for 2017 to 2022.

By default, the NASS CDL crops of sweet corn and triticale will be treated the same as corn and rye, respectively. Additionally, NASS CDL double crop categories (example: double crop winter wheat/soybeans) will be modeled for each crop separately then summed to represent the N fertilizer recommended for that year. Given that 22 crops are currently included for potential analysis in the toolbox, not all double crop systems will be represented by both crops explicitly. An example is a field growing “double crop lettuce/durum wheat”, for which lettuce is not currently included as a potential crop. In this example, N fertilizer will be calculated for only the durum wheat portion of the rotation, assuming that durum wheat is selected by the user.

For each field and year specified, the tool will calculate the lbs of N fertilizer recommended using the following equation:

- $N \text{ fertilizer (in lbs)} = \text{field acres} * N \text{ recommended (in lbs/acre) for crop grown}$

**Output Nitrogen Fertilizer Table**

ATTRIBUTES	DESCRIPTION
<b>FBndID</b>	Field boundary ID. Can be used to join to field boundary feature class.
<b>Nfert'xx'</b>	Lbs of Nitrogen fertilizer recommended on each field for each year specified, where 'xx' equals the last two digits of each year (“nfert17” equals N fertilizer recommended in 2017). A 'Nfert' field will be added for each year specified.
<b>Nfert'x'Yr</b>	Total lbs of N fertilizer recommended on each field across all years specified.
<b>Nfert'x'YrAnn</b>	Average annual lbs of N fertilizer recommended on each field. Calculated by summing the lbs of N fertilizer recommended across all years specified then dividing by the number of years.

## MANURE APPLICATION

**TIMEFRAME.** Two timeframe options are provided for the modeling of manure application and include:

### 1. Apply Manure - Across a Rotation.

Manure is applied to meet field nutrient needs over the course of a crop rotation. This is defined by an **average annual** nutrient need for each field.

This option should be chosen when modeling manure application at a P rate. Due to the imbalance between crop nutrient needs and the N:P ratio of manure, applying manure to meet the N needs of a crop will often overapply P (Sharpley et al. 2004). This can lead to a buildup of soil P over time, which can pose a threat to nearby surface waters.

Several options exist for managing a P-based manure application. One option is to apply manure to meet the full N need of a crop during year one, then apply no manure for several follow-on years to draw down soil P levels. An alternative option is to apply manure to not exceed the amount of P removed each year, which often requires supplementing with commercial fertilizer to meet the N needs of the crop. Regardless of which P approach is selected the goal is the same in that field P need is not to be exceeded over the course of a rotation (Karimi et al. 2018).

To represent P removal across a rotation, the lbs of P removed from each field is summed for each year in a rotation then dividing by the number of years. This value is derived from running the "Calculate Field Nutrient Removal: Nitrogen and Phosphorus" tool and is represented by the "Prem'x'YrAnn" attribute field, where 'x' equals the number of years specified. Modeling manure application to meet the average annual lbs of P removed from each field will provide an estimate of the land base required for manure application to occur at a P removal rate across the rotation.

The "Apply Manure – Across a Rotation" tool can also be run when modeling manure application at a N rate (either N removal or N fertilizer) when residual N is either unknown or not a concern. In most (if not all) instances, the "Apply Manure – Single Year" tool should be chosen for N-based manure application to account for the residual manure N that is mineralized and becomes crop available in the year following initial manure application.

### 2. Apply Manure - Single Year.

Manure is applied to meet field nutrient needs for a single year at a time (**annual** nutrient need) for several years in succession. Results from each year are then summarized across a crop rotation. The primary benefit of this approach is that it enables residual manure N (second year availability of manure N) to be tracked and appropriately credited year to year.

Manure application that occurs at a N rate must appropriately track and credit the residual manure N that is not immediately available following manure application (Cusick et al. 2006). The timing of manure N availability is dependent on the ratio of ammonium (NH<sub>4</sub><sup>+</sup>) vs organic N of the manure applied. Liquid manure (such as swine manure stored in below-building pits) has high levels of NH<sub>4</sub><sup>+</sup> and therefore most of the N in the manure is available immediately following application. In contrast, the NH<sub>4</sub><sup>+</sup> in manure with high organic matter (such as solid cattle manure or manure with

added bedding) takes longer to breakdown, and residual manure N can be an important source of nutrients in subsequent years.

To model manure application for a single year at a time, each field's nutrient need is defined by the lbs of N removed, P removed, or N fertilizer recommended during a single crop year. If residual manure N is remaining on a field from a previous manure application, that amount is credited (i.e. subtracted) from the nutrient requirements of the field.

### **Spatial Approach**

The process for spatial allocating manure remains the same regardless of which rate or timeframe is selected. The program runs as a series of manure application loops. The initial loop begins by selecting, for each feedlot provided, the single nearest field (based on a Euclidean distance measure) with a nutrient need greater than zero. Each feedlot can apply manure to a single field during any given loop. Using each feedlot as a source of available nutrients, manure application is simulated by decrementing the amount of nutrients required by the field from the source feedlot. Accounting is performed to track how much of each nutrient is applied during each loop of manure application. If a feedlot can meet the entire nutrient requirements of a field, that amount of the corresponding nutrient is subtracted from the amount of available from the feedlot. Once the total nutrient requirement of a field has been met, the field is no longer eligible to receive manure from any feedlot.

Alternatively, if a feedlot is only able to partially supply the nutrient needs of a field, the new nutrient requirement of the field becomes the initial requirement minus what was applied during the current loop. Once a feedlot has disposed of the entirety of its manure, it is removed from the analysis. During each application loop, the single nearest field that is still eligible to receive manure from any remaining feedlot is selected. It is possible, though uncommon, that multiple feedlots will apply manure to the same field (Porter and James, 2020).

**IMPORTANT:** Manure application may be modeled from hundreds or thousands of feedlots to thousands of agricultural fields. The process is therefore computationally intensive, and the next two tools may take anywhere from a few minutes to a few hours to run, dependent on the size of the input datasets, the computational capacity of the system, and the number of application loops required.

### 3. Apply Manure to Fields – Across a Rotation

Required Inputs	Outputs
Input Layer: Animal Feeding Operations (point feature class) containing attribute fields with lbs of crop available N and P.	Output Manure Processed Field Boundary Feature Class: 'ProcFB_Rotation_XXXXApp', where 'XXXX' equals the manure application approach selected. ('XXXX' can equal: 'NRem', 'Prem', or 'NFert')
Input Field: Unique ID field for Animal Feeding Operations	Output AFO Statistics Table: 'ProcAFO_Rotation_XXXXApp', where 'XXXX' equals the manure application approach selected. ('XXXX' can equal: 'NRem', 'Prem', or 'NFert')
Input Field: Lbs of Manure N Availability	
Input Field: Lbs of Manure P Availability	
Input Layer: Field boundaries (must contain "FBndID" and "Acres" field)	
Manure Application Approach (user selection)	
Input Table: Table containing Annual Average N or P rates	
Input Field: Field containing Annual Average N or P rates	

The intent of this tool is to model manure application over the course of a crop rotation using an **average annual** field nutrient need. It is recommended that the "Apply Manure - Across A Rotation" option be chosen when modeling manure application at a P removal rate, although there may be circumstances when the user would like to model a N-based application, such as when residual manure N is either unknown or is not a concern. This tool is designed to be run once, and results will represent manure application across a crop rotation.

Input animal feeding operations should include several attribute fields, including:

1. A unique identifier for each operation.
2. Lbs of crop-available N for each operation. Year one N availability is recommended.
3. Lbs of crop-available P for each operation. Year one P availability is recommended.

The user must select the manure application approach (N fertilizer, N removal, or P removal) when running the tool. As mentioned above, it is recommended to run the "Across A Rotation" tool when modeling for a P-based manure application approach. The user must also provide a table that contains **annual average N or P nutrient needs for each field**. Determining which table to provide will depend on the user selected manure application approach.

If a N rate approach is selected, the table will be either:

- Nutrient Removal table (output from "1b. Calculate Field Nutrient Removal")
- Nitrogen Fertilizer table (output from "2. Calculate Nitrogen Fertilizer Input")

If a P rate approach is selected (recommended), the table will be:

- Nutrient Removal table (output from "1b. Calculate Field Nutrient Removal")

From the provided table, the user must specify which attribute field contains the lbs of average annual nutrient need of each field. The values in the specified attribute field represent how much manure will be applied to each field.

If a N rate approach is selected, the attribute field will be either:

- nremxYrAnn: annual average lbs of N removed, 'x' equals number of years in crop rotation.
- nfertxYrAnn: annual average lbs of N fertilizer, 'x' equals the number of years in crop rotation.

If a P rate approach is selected (recommended), the attribute field will be:

- premxYrAnn: annual average lbs of P removed, 'x' equals number of years in crop rotation.

**IMPORTANT:** Estimates of crop-available manure N and P are used to generate a N:P ratio for each animal feeding operation. As manure P is applied to meet the lbs of P removed by the field, N is also applied according to the unique N:P ratio of the feedlot (or vice versa if a N rate is selected). The lbs of N and P applied to each field is tracked during each manure application loop as well as decremented from the available nutrients of the feedlot.

**IMPORTANT:** This tool does not track residual (Year Two) manure N availability. As the tool models manure application to meet an **average annual nutrient need** of each field, it does not allow for the tracking of residual manure N remaining on each field from year to year. If tracking and appropriately crediting residual manure N is important to the user, it is recommended to run the "Apply Manure to Fields – Single Year" tool.

Tool outputs includes a manure processed field boundary feature class ('ProcFB\_Rotation\_xxxxApp') and a AFO Statistics Table ('ProcAFO\_Rotation\_xxxxApp') where 'xxxx' equals the manure application approach selected: 'NRem', 'Prem', or 'NFert').

**IMPORTANT:** It is important to verify the coordinate system of all input feature classes. A coordinate system with horizontal units in meters (such as UTM) is recommended. The output AFO Statistics Table includes the distance from each operation to the furthest field where manure was applied. This is calculated as both a straight-line (Euclidean) distance ("maxEUDist") and Manhattan distance ("maxMHdist"). The units for both distance calculations will be the same units as the coordinate system of the input feedlot feature class.

**Output Manure Processed Field Boundary Feature Class.**

N Rate Chosen (N removal rate or N fertilizer)	
ATTRIBUTES	DESCRIPTION
<b>Nneed</b>	Field N need (in lbs): average annual lbs of N removed or lbs of N fertilizer recommended. Calculated by summing field N need for each year in the rotation then dividing by the number of years.
<b>Napp</b>	Manure N applied (in lbs) to meet field N needs.
<b>Done</b>	1-all field N need met by manure, 0-no N need meet by manure, 99999-partially met.
<b>Papp</b>	Manure P applied (in lbs).
<b>PctNUsed</b>	Percent of field N need met by manure.
<b>ManAcres</b>	Acres receiving manure (PctNUsed * field acreage).

- **Nneed:** The average annual field N need as defined by the user-provided attribute field. Manure application occurs on only those fields with an N need greater than zero. Manure is applied to meet either:
  - the **average annual lbs** of N removed from each field (N removal approach, input attribute field should be 'nremxYrAnn', where 'x' equals the number of years in the crop rotation).
  - the **average annual lbs** of N fertilizer recommended for each field (N fertilizer approach, input attribute field should be 'nfertxYrAnn, where 'x' equals the number of years in the crop rotation).

- **Napp:** Manure N (in lbs) applied to meet the average annual field N need. Note that the ‘Across a Rotation’ approach does not allow for the modeling of residual N. By modeling manure application to meet the average annual field N need, this includes years with a field N need and years without.  
  
Using an alternating corn-soybean field (“CBCBCB”) across a six-year rotation and an N fertilizer approach as an example, the average annual field N need is found by taking the N need for each corn year (150 lbs/acre for corn following soybean) plus the N need for each soybean year (0 lbs/acre), then dividing by six years:  $((150*3 \text{ years}) + (0*3 \text{ years})) / 6 = \text{average annual field N need of 75 lbs/acre.}$
- **Done:** A value to classify if the field N need was fully (1), partially (999999), or not at all (0) met by manure. By applying to meet the average annual field N need, a value of ‘1’ would indicate that the full N need of the field across its crop rotation has been met by manure.
- **Papp:** The lbs of manure P applied as manure is applied at a N rate.
- **PctNUsed:** The percent of each field’s N need across the crop rotation that was met by manure. Calculated by:  $(\text{‘Napp’} / \text{‘Nneed’}) * 100.$
- **ManAcres:** Acres for which manure met field N need. Calculated by:  $(\text{“PctNUsed”} / 100) * \text{acreage of field.}$

P Rate Chosen (P removal)	
ATTRIBUTES	DESCRIPTION
<b>Pneed</b>	The average annual lbs of P removed from each field. Calculated by summing field P need for each year in the rotation then dividing by the number of years.
<b>Papp</b>	Manure P applied (in lbs) to meet field P need.
<b>Done</b>	1-all field P need met by manure, 0-no P need meet by manure, 99999-partially met.
<b>Napp</b>	Manure N applied (in lbs).
<b>PctPUsed</b>	Percent field P need met by manure.
<b>ManAcres</b>	Acres receiving manure $(\text{PctPUsed} * \text{field acreage}).$

- **Pneed:** The average annual field P need as defined by the user-provided attribute field. Manure application occurs on only those fields with a P need greater than zero. Manure is applied to each field to meet:
  - the **average annual lbs** of P removed from each field (P removal approach, input field should be ‘PremxYrAnn’, where ‘x’ equals the number of years specified).
- **Papp:** Manure P applied (in lbs) to meet the average annual field P need. By applying manure to meet the average annual field P need, this includes years where P is removed and years where it is not. A crop that is not harvested (such as fallow) represents a year in which P removal will equal zero.
- **Done:** A value to classify if the field P need was fully (1), partially (999999), or not at all (0) met by manure. By applying to meet the average annual field P need, a value of ‘1’ would indicate that the full P need of the field across its crop rotation has been met by manure.
- **Napp:** The lbs of manure N applied as manure is applied at a P rate.
- **PctPUsed:** The percent of each field’s P need across the crop rotation that was met by manure. Calculated by:  $(\text{‘Papp’} / \text{‘Pneed’}) * 100.$
- **ManAcres:** Acres for which manure met field P need. Calculated by:  $(\text{“PctPUsed”} / 100) * \text{acreage of field.}$

**Output AFO Statistics Table**

<b>ATTRIBUTES</b>	<b>DESCRIPTION</b>
<b>Manure N Availability</b>	Lbs of manure N available at each location. Defined by the user-provided "Input Field: Manure N Availability" in the tool interface.
<b>Manure P Availability</b>	Lbs of manure P available at each location. Defined by the user-provided "Input Field: Manure P Availability" in the tool interface.
<b>Done</b>	1-no manure nutrients remaining, 0-manure nutrients remaining.
<b>fldcnt</b>	Number of fields that were modeled to receive manure from each location.
<b>maxEUDist</b>	Maximum Euclidean distance (in same coordinate system as input feedlot feature class) of the furthest field to which manure nutrients were applied.
<b>maxMHdist</b>	Maximum Manhattan distance (in same coordinate system as input feedlot feature class) of the furthest field to which manure nutrients were applied.

#### 4a. Apply Manure to Fields – Single Year

Required Inputs	Outputs
Input Layer: Animal Feeding Operations (point feature class) containing attribute fields with lbs of crop available nutrients (N and P).	Output Manure Processed Field Boundary Feature Class: 'ProcFB_Rotation_XXXXApp', where 'XXXX' equals the manure application approach selected. ('XXXX' can equal: 'NRem', 'Prem', or 'NFert')
Input Field: Unique ID field for Animal Feeding Operations	Output AFO Statistics Table: 'ProcAFO_Rotation_XXXXApp', where 'XXXX' equals the manure application approach selected. ('XXXX' can equal: 'NRem', 'Prem', or 'NFert')
Input Field: Lbs of Manure N Available Year One	
Input Field: Lbs of Manure N Available Year Two	
Input Field: Lbs of Manure P Available	
Input Layer: Field boundaries (must contain "FBndID" and "Acres" field)	
Input Field: Lbs of residual manure N (from previous year's application) (optional)	
Manure Application Approach (user selection)	
Current Processing Year	
Input Table: Table containing Annual N or P rates	
Input Field: Field containing Annual N or P rates	
Create New FB Output? (optional) (should be selected for only for the first processing year).	

The intent of this tool is to model manure application over the course of a crop rotation but with each year processed in singularity. The primary benefit of this approach is the ability to account for residual manure N that may exist on a field from a previous year's manure application. Therefore, this tool is most applicable when selecting a N-based application rate to enable the tracking of residual (Year 2 manure N availability) over time.

This tool is designed to be run separately for several years in succession. Importantly, the output manure processed field boundary feature class from the first processing year should serve as the input field boundary feature class for all subsequent processing years.

Most regulatory scenarios that utilize a P application approach, in contrast, are based on not exceeding the lbs of P removed from a field over the course of its crop rotation. It is therefore suggested to use the "Apply Manure to Fields – Across a Rotation" tool when modeling manure application using a P-based approach.

Input animal feeding operations should include several attribute fields, including:

1. A unique identifier for each operation.
2. Lbs of year one crop-available N for each operation.
3. Lbs of year two crop-available N for each operation.
4. Lbs of crop-available P for each operation. Year one P availability is recommended.

The user must specify the current processing year as well as the manure application approach (N fertilizer, N removal, or P removal). The user must provide a table that contains **annual N or P needs for**

**each field.** Determining which table to provide will depend on the user selected manure application approach.

If a N rate approach is selected, the table will be either:

- Nutrient Removal table (output from “1b. Calculate Field Nutrient Removal”)
- Nitrogen Fertilizer table (output from “2. Calculate Nitrogen Fertilizer Input”)

If a P rate approach is selected, the table will be:

- Nutrient Removal table (output from “1b. Calculate Field Nutrient Removal”)

From the provided table, the user must specify which attribute field contains the **annual nutrient need of each field.** The values in the attribute field represent how much manure will be applied to each field.

If a N rate approach is selected, the attribute field will be either:

- Nrem'xx': annual lbs of N removed, 'xx' equals the last 2 digits of the current processing year.
- Nfert'xx': annual lbs of N fertilizer, 'xx' equals the last 2 digits of the current processing year.

If a P rate approach is selected, the attribute field will be:

- Prem'xx': annual lbs of P removed, 'xx' equals the last 2 digits of the current processing year.

**IMPORTANT: A new output feature class should be created only for the first year processed.** By default, the “Create New FB Output” will be selected and should be unselected for all subsequent year model runs. When selected, the name of the output feature class will be “ProcFB\_”method”\_”year”, where method equals the manure application approach (“NRemApp”, “NFertApp”, or “PRemApp”) and year equals the current processing year.

**The “Create New FB Output” should be unselected for all subsequent year model runs.** Instead, the output feature class that is created during the initial processing year should be provided as the input field boundaries for all subsequent years, and all attribution will be appended as new fields to that feature class. By unselecting the “Create New FB Output” for subsequent year model runs, the file name of the output manure processed feature class will be represented by the first year that manure application was modeled.

**IMPORTANT:** There will be no residual manure N from a previous application during the first processing year. If 2017 is chosen as the first year, for example, the current processing year will be 2017 and the residual manure N field will be left blank. For subsequent year model runs, the attribute field containing the residual N from the previous year’s application should be provided as the “Residual Manure N field”. With an example current processing year of 2018, the residual N attribute field from 2017 (“ResidualN2017”) should be provided to represent the year two N that was applied in 2017 and will become available in 2018. Any field with a N need in 2018 will first be credited by the amount of residual manure that is present on the field.

The user may decide to run the tool for a “warmup” year if the goal is to summarize manure application over a specific time-period. This will ensure that residual manure N has been accounted for in all years. For example, if a user would like to summarize manure application between 2017 and 2022, the tool may be run for each year between 2016 to 2022 (using 2016 as a warmup year) then summarize results for 2017 to 2022.

Although rare, there is the possibility for residual manure N to exceed the N need of a field in the current processing year. An example is a crop rotation in which a crop with a low N need (such as a small grain)

follows a crop with a high N need (such as corn). This situation is more frequently encountered when the manure source is high in organic matter, causing a significant amount of the manure N to become available in the year following application.

When manure is applied to meet the full N need of the crop with a high N need, the amount of residual manure N remaining on the field may exceed the N need of the subsequent crop. While no additional manure will be applied (all residual N is credited to the field), there may still be an “excess” of manure N above the need of the field. This situation is identified by a “PctNUsed” value > 100 for any of the processing years. When this occurs, the “ManAcres” is set to the acreage of the field for that year.

**IMPORTANT:** If a P removal rate is selected, the amount of year two manure N applied is tracked for each year. However, since manure application is not occurring at a N rate, the residual N on a field is not deducted (“credited”) from a field’s nutrient need.

**IMPORTANT:** It is important to verify the coordinate system of all input feature classes. A coordinate system with horizontal units in meters (such as UTM) is recommended. The output AFO Statistics Table includes the distance from each operation to the furthest field where manure was applied. This is calculated as both a straight-line (Euclidean) distance (“maxEUdist”) and Manhattan distance (“maxMHdist”). The units for both distance calculations will be the same units as the coordinate system of the input feedlot feature class.

Tool outputs in the first processing year include a manure processed field boundary feature class (‘ProcFB\_‘xxx\_‘yyyy’) and a AFO Statistics table (‘ProcAFO\_‘xxx\_‘yyyy’) where ‘xxx’ equals the manure application approach selected (‘NRem’, ‘Prem’, or ‘NFert’) and ‘yyyy’ equals the current processing year. A new manure processed field boundary feature class should be not created for subsequent processing years. Instead, the output manure processed field boundary feature class from the first processing year should be provided as the input field boundaries to all subsequent model runs, to which all attribution will be appended as new fields. In contrast, a new output AFO statistics table will be created for each year processed.

**Output Manure Processed Field Boundary Feature Class.**

N Rate Chosen (N removal rate or N fertilizer) (‘xx’ indicates current processing year)	
ATTRIBUTES	DESCRIPTION
Nneed‘xx’	Field N need: annual lbs of N removed or annual lbs of N fertilizer recommended.
Napp‘xx’	Lbs of year one manure N applied during current processing year (excludes residual N from a previous application and year two N applied during current processing year).
Nresidual‘xx’	Lbs of year two manure N applied (will become available the following year) during current processing year.
Done‘xx’	1-all field N need met by manure, 0-no N need meet by manure, 99999-partially met. A value of 1 is assigned if year one manure N applied (from current processing year) plus residual N (from previous application) met the field N need.
Papp‘xx’	Lbs of manure P applied as manure is applied at a N rate.
PctNUsed‘xx’	Percent field N need met by manure. Includes year one manure N applied (from current processing year) plus any residual N (from previous application) existing on a field.
ManAcres‘xx’	Acres receiving manure (PctNUsed * field acreage).

- **Nneed:** Field N need (in lbs) in the current processing year. Manure application occurs on only those fields with a N need greater than zero. Manure is applied to each field to meet either:
  - the **annual** lbs of N removed from each field (N removal approach, input attribute field should be 'nremxx', where 'xx' equals the last two digits of the current processing year.
  - the **annual** lbs of N fertilizer recommended for each field (N fertilizer approach, input attribute field should be 'nfertxx', where 'xx' equals the last two digits of the current processing year.
- **Napp:** Year one manure N (in lbs) applied to meet field N need in the current processing year. This does not include residual N from a previous application or year two manure N that will become available in subsequent years. Note that if residual N exists on a field from a previous application, this is subtracted ("credited") from the field N need prior to manure application using year one nutrients.
- **NResidual:** The lbs of year two manure N that is applied during the current processing year and will become available the following year.
- **Done:** A value to classify if the field N need was fully (1), partially (999999), or not at all (0) met by manure in the current processing year. This includes both year one N applied and any residual N remaining on the field from a previous application. Note that if manure is not applied to a field in the current processing year (Napp = 0), the "Done" value can still be > 0 if residual N exists on the field and the field has a N need.
- **Papp:** The lbs of manure P applied during the current processing year as manure is applied at a N rate.
- **PctNUsed:** Percent of field N need that was met by manure in the current processing year. This includes year one manure N applied during the current processing year as well as any residual N remaining on the field from a previous application. Note that if manure is not applied to a field in the current processing year (Napp = 0), the "PctNUsed" can still be > 0 if residual N exists on the field and the field has a N need.
- **ManAcres:** Acres for which manure met the field N need in the current processing year. Calculated by: ("PctNUsed" / 100) \* acreage of field. This includes year one N applied during the current processing year as well as residual N remaining on the field from a previous application. Note that if manure is not applied to a field in the current processing year (Napp = 0), the "ManAcres" can still be > 0 if residual N exists on the field and the field has a N need. These are considered manured acres as manure is meeting the field N need and should therefore be appropriately credited. Importantly, this calculation excludes acres for which residual N exists on a field without a N need in the current processing year.

P Rate Chosen (P removal) (xx' indicates the current processing year)	
ATTRIBUTES	DESCRIPTION
<b>Pneed'xx'</b>	Field P need (in lbs): annual lbs of P removed.
<b>Papp'xx'</b>	Lbs of manure P applied.
<b>Done'xx'</b>	1-all field P need met by manure, 0-no P need meet by manure, 99999-partially met. A value of 1 is assigned if manure P applied (from current processing year) met the field P need.
<b>Napp'xx'</b>	Lbs of year one manure N applied.
<b>NResidual'xx'</b>	Lbs of year two manure N applied (will become available the following year).
<b>PctPUsed'xx'</b>	Percent field P need met by manure.
<b>ManAcres'xx'</b>	Acres receiving manure (PctPused * acres of field)

- **Pneed:** The lbs of P removed from each field in the current processing year, as defined by the user-provided attribute field. Manure application occurs on only those fields with a P need greater than zero.

- **Papp:** The amount of manure P applied to meet the P need of each field.
- **Done:** A value to classify if the field P need was fully (1), partially (999999), or not at all (0) met by manure in the current processing year.
- **Napp:** The lbs of year one manure N applied during the current processing year as manure is applied at a P rate.
- **NResidual:** The lbs of year two manure N applied during the current processing year as manure is applied at a P rate.
- **PctPUsed:** The percent of each field’s P need that was met by manure in the current processing year.
- **ManAcres:** Acres for which manure met field P need. Calculated by: (“PctPUsed” / 100) \* acreage of field.

**Output AFO Statistics Table**

ATTRIBUTES	DESCRIPTION
<b>Manure N Year One Availability</b>	Lbs of year one manure N available at each location. Defined by the user-provided “Input Field: Manure N Year One” in the tool interface.
<b>Manure N Year Two Availability</b>	Lbs of year two manure N available at each location. Defined by the user-provided “Input Field: Manure N Year Two” in the tool interface.
<b>Manure P Availability</b>	Lbs of manure P available at each location. Defined by the user-provided “Input Field: Manure P Availability” in the tool interface.
<b>Done</b>	1-no manure nutrients remaining, 0-manure nutrients remaining.
<b>fldcnt</b>	Number of fields that were modeled to receive manure from each location.
<b>maxEUDist</b>	Maximum Euclidean distance (in same coordinate system as input feedlot feature class) of the furthest field to which manure nutrients were applied.
<b>maxMHdist</b>	Maximum Manhattan distance (in same coordinate system as input feedlot feature class) of the furthest field to which manure nutrients were applied.

#### 4b. Summarize Manure Application by Year

Required Inputs	Outputs
Input Layer: Manure Processed Field Boundary Feature Class (output from 5a. Apply Manure to Fields – Single Year)	Output By-Year Manure Summary 'ManureSummary_XXXX_YYYY_ZZZZ', where 'XXXX' equals the first year, 'YYYY' equals the last year, and 'ZZZZ' equals the manure application approach selected ('NRem', 'Prem', or 'NFert').
First Year (user selection)	
Last Year (user selection)	
Manure Application Approach (user selection)	

This tool provides a summary of the “Apply Manure to Fields – Single Year” tool and should only be run when the previous tool has been run for several subsequent years. The user must select from the input manure processed field boundary feature class (output from 5a. Apply Manure to Fields – Single Year”) the first and last year of the rotation that the user would like to summarize.

#### Output Manure Summary Table

N Rate Chosen (N removal rate or N fertilizer)	
ATTRIBUTES	DESCRIPTION
<b>manureYears</b>	Number of years manure was applied to each field.
<b>Nneedann</b>	Average annual lbs of field N need.
<b>Nappann</b>	Average annual lbs of year one manure N applied.
<b>manureNaccumulatedann</b>	Average annual lbs of manure N (year one N + residual N from a previous application) used by crops with an N need where manure is applied (Nneed > 0 and Napp > 0).
<b>residualNaccumulatedann</b>	Average annual lbs of residual manure N (from a previous application) used by crops with an N need where manure is not applied (Napp=0).
<b>residualNnonaccumulatedann</b>	Average annual lbs of residual manure N remaining on fields without an N need (Nneed=0).
<b>manureNann</b>	Average annual lbs of crop-available manure N.
<b>Pappann</b>	Average annual lbs of manure P applied.
<b>PctNUsedtot</b>	Percent of total field N need satisfied by manure across all years specified.
<b>manureAcresann</b>	Manured acres in an average year.
<b>manureAcrestot</b>	Manured acres across all years specified.
<b>Done</b>	1-all field N need met by manure, 0-no N need meet by manure, 99999-partially met.

  

<ul style="list-style-type: none"> <li>• <b>manureYears:</b> The number of years that manure was applied to each field. Does not include years that residual manure N existed on a field but no manure was applied.</li> <li>• <b>Nneedann:</b> Average annual field N need (in lbs). Calculated by summing field N need for each year specified, then dividing by the number of years.</li> <li>• <b>Nappann:</b> Average annual lbs of year one manure N applied. Calculated by summing year one manure N applied (excludes residual N from a previous application or year 2 N applied) for each year specified, then dividing by the number of years.</li> <li>• <b>ManureNaccumulatedann:</b> Average annual lbs of manure N <i>used by fields with a N need where manure was applied</i>. Calculated by summing year one manure N applied and residual manure N (from a previous</li> </ul>
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application) for each field that received manure for each year specified. This sum is then divided by the number of years. This excludes residual N used by fields with a N need but that had no manure applied.

- **ResidualNaccumulatedann:** Average annual lbs of residual manure N *used by crops with a N need but that had no manure applied*. Calculated by summing the residual manure N for all fields with a N need but that had no manure applied for each year specified, then dividing by the number of years.
- **ResidualNnonaccumulatedann:** Average annual lbs of residual manure N remaining on fields *without a N need and that had no manure applied*. Calculated by summing the residual manure N existing on fields without a N need and no manure applied for each year specified, then divided by the number of years.

**Example:** Assume a N fertilizer approach with the N need of legumes set to zero. The “residualNnonaccumulatedann” represents the average annual lbs of residual N remaining on fields without a N need, in this case legumes. If a N removal rate is selected, however, legume N need will equal the N removal rate, and therefore the residual N would be included in either the “ManureNaccumulatedann” field (if manure was applied to field) or “ResidualNaccumulatedann” field (if manure was not applied to field).

- **ManureNann:** Average annual lbs of *crop-available* manure N. Includes year one manure N applied plus residual manure N available on any field, regardless of field N need or if manure was applied. This value is summed for each year specified then divided by the number of years. Represents total crop-available manure N in an average year and should equal the lbs of crop-available N (year one + two) from all feedlots.
- **Pappann:** Average annual lbs of manure P applied. Calculated by summing the manure P applied for each year specified, then dividing by the number of years.
- **PctNUusedtot:** Percent of total field N need that was met by manure across all years specified. Calculated by summing manureNaccumulated + residualNaccumulated for each year specified, then dividing by the total field N need across all years. This value may occasionally exceed 100% when residual manure N on a field exceeds the crop N need. If the value exceeds 100%, the manure acres is set to the acreage of the field.
- **ManureAcresann:** Acres whose N need was met by manure in an average year. Calculated by summing the manured acres for each year specified, then dividing by the number of years. Represents the required crop acres for manure nutrient assimilation *in an average year*.
- **ManureAcrestot:** Acres whose N need was met by manure across all years specified. Calculated by: (“PctNUusedtot” / 100) \* acreage of field. This includes the sum of year one manure N applied and residual manure N (from a previous application) for all fields and years with an N need, regardless of whether manure was applied to the field during each processing year. Importantly, this calculation excludes residual manure nutrients remaining on a field without a N need (“ResidualNnonaccumulated”). This value represents the total required crop acres for manure nutrient assimilation *across the crop rotation*.
- **Done:** A value to classify if the total field N need was fully (1), partially (999999), or not at all (0) met by manure across all years of the rotation. This is determined by the “PctNUusedtot” field.

Attribute Fields if P Rate Chosen (P removal)	
ATTRIBUTES	DESCRIPTION
manureYears	Number of years manure was applied to each field.
Pneedann	Average annual lbs of field P need.
Pappann	Average annual lbs of manure P applied.
Nappann	Average annual lbs of manure N (year one) applied.

<b>residualNappann</b>	Average annual lbs of manure N (year two) applied.
<b>PctPUse dtot</b>	Percent of total field P need satisfied by manure across all years specified.
<b>manureAcresann</b>	Manured acres in an average year.
<b>manureAcres tot</b>	Manured acres across all years specified.
<b>Done</b>	1-all field P need met by manure, 0-no P need meet by manure, 99999-partially met.

- **Manure Years:** The number of years that manure was applied to each field.
- **Pneedann:** Average annual field P need (in lbs). Calculated by summing the field P need for each year specified, then dividing by the number of years.
- **Pappann:** Average annual lbs of manure P applied. This is calculated by summing manure P applied for each year specified, then dividing by the number of years.
- **Nappann:** Average annual lbs of year one manure N applied. Calculated by summing year one manure N applied for each year specified, then dividing by the number of years.
- **ResidualNappann:** Average annual lbs of year two manure N applied. Calculated by summing the year two manure N applied for each year specified, then dividing by the number of years.
- **PctPUse dtot:** Percent of total field P need that was met by manure across all years specified. Calculated by summing manure P applied for each year specified, then dividing by the total field P need across all years.
- **ManureAcresAnn:** Acres whose P need was met by manure in an average year. Calculated by summing manured acres for each year specified, then dividing by the number of years. Represents the required crop acres for manure nutrient assimilation *in an average year*.
- **ManureAcresTot:** Acres whose P need was met by manure across all years. Calculated by: (“PctPUse dtot” / 100) \* acreage of field. Represents the total required crop acres for manure nutrient assimilation *across the crop rotation*.
- **Done:** A value to classify if the total P need of each field was fully (1), partially (999999), or not at all (0) met by manure across all years of the rotation. This is determined by the “PctPUse dtot” field.

## INTEPRETING RESULTS

### Mapping Manure Application

The simplest way to visualize the results of any manure application scenario is to use the “Done” attribute field, which is created regardless of which application rate or timeframe is selected. A value of “0” indicates that no manure was applied to a field, a value of “1” indicates that the nutrient need of the field was entirely met by manure, and a value of “999999” indicates that manure was applied to the field but did not fully meet the nutrient need of the field. Symbolizing the output manure processed field boundary feature class by the “Done” field provides a simple and straightforward way to visualize which fields that were modeled to receive manure nutrients.

When running the “Apply Manure – Single Year” tool, a “Done” attribute field will be created for each processing year in the output manure processed field boundary feature class. The attribute field will be named “Done’xx’”, where ‘xx’ equals the last two digits of the current processing year. The “Done” field indicates if the field’s nutrient need was met by manure in just that processing year.

When summarizing several years of manure application in succession (“Summarize Manure Application by Year”), a “Done” attribute field (without any suffix) will exist in the output summary table and indicates if the field’s total nutrient need over the course of the rotation has been entirely (“1”), partially (“999999”), or not at all (“0”) met by manure. A field’s nutrient need may be fully met by manure during a single processing year but only partially met over the crop rotation.

When running the “Apply Manure – Across a Rotation” tool, a “Done” attribute field (without any suffix) will be created in the output manure processed field boundary feature class. The “Done” field indicates if the field’s total nutrient need over the course of the rotation has been entirely (“1”), partially (“999999”), or not at all (“0”) met by manure.

The user may also wish to visualize results using the “PctNUsed” or “PctPUsed” attribute field, which is created regardless of which application rate or timeline is selected. Values in this field represent the percent of field nutrient need satisfied by manure and provides more detail than the “Done” field. While a “Done” value of “999999” will indicate that a field’s nutrient need was only partially met by manure, for example, this may range from 1 to 99%.

Note that in rare cases, values for “PctNUsed” may exceed 100%, a situation that can occur when the residual manure N on a field exceeds the field N need. When manure is applied to meet the full N need of a crop with a high N fertilizer requirement, for example, the amount of residual manure N remaining on the field may exceed the full N requirement of the subsequent crop. This situation is only possible when modeling a N-based manure application rate for a single year at a time. It is more frequently encountered when the manure source is high in organic matter, causing a significant amount of the manure N to become available in the year following application.

When running the “Apply Manure – Single Year” tool, a “PctNUsed” or “PctPUsed” attribute field will be created for each year processed in the output manure processed field boundary feature class. The attribute field will be named “Pct’x’used’yy’”, where ‘x’ equals the nutrient that manure application was based on and ‘yy’ equals the last two digits of the current processing year.

When summarizing several years in succession (“Summarize Manure Application by Year”), a “PctNUstedtot” or “PctPUstedtot” attribute field will exist in the output summary table and represents the percent of the field’s total nutrient need that was met by manure over the course of the rotation. A field’s nutrient need may be fully met during a single processing year but only partially met over the crop rotation.

When running the “Apply Manure – Across a Rotation” tool, a “PctNUsted” or “PctPUsted” attribute field (without any suffix) will be created in the output manure processed field boundary feature class. The “PctNUsted” or “PctPUsted” field represents the percent of the field’s total nutrient need that was met by manure over the course of the crop rotation.

### **Calculating Land Application Base**

The timeframe selected has a large impact on estimating the required crop acreage for manure nutrient assimilation, and the required land base can change significantly dependent on if the user is modeling for a single year or across a crop rotation. The number of crop acres required for manure nutrient assimilation will typically increase when modeling across a crop rotation, as not every field is eligible to receive manure every year.

An example is an alternating corn soybean rotation with the assumption that no manure is applied to soybeans. When modeling manure application for a single year, acreage is limited to those fields planted to corn. In the following year, however, those same fields may be planted to soybeans and therefore are no longer eligible to receive manure. In this scenario, the land base required over a crop rotation would be double the land base required for manure application in just a single year. This is an important consideration when estimating the required land base for manure application and will vary dependent on the agricultural system and the dominant crop rotations in the area of interest.

When running the “across the rotation” tool, the “ManAcres” attribute field in the output manure processed field boundary feature class indicates the required acreage for manure application across the crop rotation.

When running the “Apply Manure – Single Year” tool, the “ManAcres” attribute field will be created for each year processed in the output manure processed field boundary feature class. The attribute field will be named “ManAcres’xx”, where ‘xx’ equals the last two digits of the current processing year. The “ManAcres” field represents the required crop acres for manure nutrient assimilation in just that processing year.

When summarizing several years in succession (“Summarize Manure Application by Year”), both a “ManAcresann” and a “ManAcresTot” attribute field will exist in the output summary table. The “ManAcresann” field represents the acres required for manure application in an average year and is calculated by summing the “ManAcres” for each year specified, then dividing by the number of years. This includes all years in the crop rotation regardless of whether the field had a nutrient need or if manure was applied.

Conversely, the “ManAcresTot” attribute field represents the total required acreage for manure application across all years of the crop rotation. This is calculated by multiplying the percent of total field nutrient need that was met by manure for all years in the rotation by the acreage of the field. Importantly, this calculation excludes acres upon which residual manure nutrients remain but are not

taken up by a crop with a nutrient need. An example is residual manure N that remains on a field planted to soybeans when the N need of soybeans is set to 0. The manure on these crop acres do not need to be credited as no N application to the field is occurring.

### Calculating Nutrient Balance

The user may wish to calculate a nutrient balance on fields that were modeled to receive manure. An example is to calculate the lbs of manure P applied above the lbs of P removed **when applying manure to meet a field N need**. The steps to complete this task are described below, and an additional calculation will need to be completed to ensure that nutrient balances are calculated for only manured acres.

To calculate P excess when running the “Apply Manure – Across a Rotation” tool, the user would use the “Papp” attribute field from the output manure processed field boundary feature class. This field represents the average annual lbs of manure P applied to each field as manure is applied at a N rate. The user would then join the “Prem’x’YrAnn” attribute field from the Nutrient Removal table to the manure processed field boundary feature class (using the “FBndID” as the join field). The “Prem’x’YrAnn” field represents the average annual lbs of manure P removed from each field. The difference between these two values is the excess P applied to each field.

While straightforward, the above example works only if manure was applied to 100% of the field. For those fields where the “PctNUsed” is less than 100% (“Done = 999999”), the tool output assumes that manure was not applied to the entirety of the field. If 40% of a field’s N need (“PctNUsed” = 40) was supplied by manure, for example, the “ManAcres” for that processing year is calculated as 40% of the field acreage.

To accurately reflect nutrient balance on partially manured fields, the user must adjust the amount of P removed from the field to equal the proportion of the field that was modeled to receive manure nutrients. To do this within the ArcGIS field calculator, the user should create a new field within the output manure processed field boundary feature class and calculate it as: ‘Prem’x’YrAnn” \* (“PctNUsed” / 100) to adjust P removal values to reflect only those acres on which manure application occurred. This will ensure that P excess is calculated only for manured acres. While partial manure application to fields is not a common practice, this calculation is required to align nutrient balances with how tool outputs are reported.

To calculate P excess when running the “Apply Manure – Single Year” tool, the user would use the “Papp’xx” attribute field in the output manure processed field boundary feature class, which represents the lbs of manure P applied to each field during the current processing year. The user would then join the “Prem’xx” attribute field from the nutrient removal table to the manure processed field boundary feature class (using “FBndID” as the join field), where ‘xx’ equals the current processing year. As described above, the user would then need to adjust the “Prem’xx” values to limit the analysis to only those acres receiving manure. To do this within the ArcGIS field calculator, the user should create a new field and calculate it as: ‘Prem’xx” \* (“PctNUsedxx” / 100) to adjust P removal values to reflect only those acres on which manure application occurred.

To calculate P excess for several years modeled in succession (“Summarize Manure Application by Year”), the user would use the “Pappann” attribute field from the output manure processed field boundary feature class. This field represents the average annual lbs of manure P applied to each field. The user

would then join the "Prem'x'YrAnn" attribute field from the nutrient removal table (using "FBndID" as the join field) to the manure processed field boundary feature class. This field represents the average annual lbs of manure P removed from each field. Using the same process described above, the user should create a new field in the output manure processed field boundary feature class and calculate it as: 'Prem'x'YrAnn" \* ("PctNUsedtot" / 100) to adjust P removal values to reflect only those acres on which manure application occurred.

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