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Description of the approach, data, and analytical methods used for the *Farms Under Threat: the State of America's Farmland* project

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Introduction

Farmers, land managers, and policy makers are greatly concerned over the loss of natural resources as land use change occurs (Brown et al. 2005). In this context, although a number of national datasets on agriculture and land use have been developed over the past decades (see Table 1), nationally consistent, high resolution spatial data on farmland location and change have been unavailable. The primary program to measure land cover and land uses change in the US is the National Resources Inventory (NRI) administered by the US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS). The advent of the NRCS NRI program in 1977 made it possible to track the conditions and trends of soil, water and related resources. NRCS conducts this statistical survey of natural resource conditions and trends on non-federal land in cooperation with Iowa State University's Center for Survey Statistics and Methodology. Among other attributes, the NRI tracks changes in land cover/use which provides critical data on how much agricultural land is developed (i.e., converted to urban land uses) and other trends affecting the nation's land and natural resources (Nusser and Goebel 1997). The precision of NRI statistical estimates vary with the number of samples involved in a particular inventory activity. Although the NRI is based on a sample of roughly 800,000 survey points, summaries at the national and state level, but summaries at finer scales (e.g., counties or watersheds) are not provided due to data limitations. Consequently, it is most applicable for monitoring state and national levels of gross land conversion (Lark et al. 2015). The NRI currently releases state level estimates to the public and is exploring ways to achieve statistical reliability for county-level sub-state estimates (Schnepf and Flanagan *pers. comm.* 2016). These periodic inventories remain the primary source of information about changes in land use in the US.

In addition to the NRI, the National Land Cover Database (NLCD) that represents land cover/use and includes general classes that are either labeled with similar class types (e.g., cropland, pastureland), or surrogates classes (e.g., privately-owned grasslands and shrublands identified as rangeland) to map agricultural land cover patterns and trends. Another source of data on national-level agricultural lands is the USDA National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL), but it does not directly map rangeland and woodland, provides data from only 2008 to 2017, is intended to map annual land cover rather than changes over time (Lark et al. 2017), and is not explicitly calibrated to estimates from the NRI on agricultural lands. Additionally, the USDA NASS Census of Agriculture (CoA) program provides information on the extent of agricultural lands, but is based on a survey of farm operators, has changed the definition over time for of several important classes that confound examining change in the recent decades, and the finest resolution of the data is at the county scale.

Because there is a growing need to understand the patterns and rates of change that better inform land use planning at land management-relevant scales, as well as to inform and motivate decision makers regarding the importance of this finite resource, American Farmland Trust and Conservation Science Partners worked together to generate the "Farms Under Threat: the State of America's Farmlands" (SAF) data and map products. The SAF program provides critical information to evaluate trends and patterns of agricultural lands in multiple ways by:

1) including a new class of agricultural lands that estimates woodlands associated with farm enterprises;
2) mapping grazing on federal lands;
3) accounting for effects of low-density residential development on agricultural lands;
4) showing the spatial patterns of agricultural land uses and conversion to development in a consistent way over time so that people can see the patterns of change; and
5) identifying agricultural lands based on their productivity, versatility and resiliency to support intensive food and crop production (i.e., 'PVR' values for lands).

Here we provide technical documentation to support the methods, results, and key data products developed for the SAF effort.

Methods

We produced two principal products for the SAF project, namely, maps and summary statistics for: (a) land cover/use, including historical, current, and change; and (b) PVR agricultural lands. These datasets are mapped on non-federal lands in the continental US. Here we describe our approach to mapping land cover/use for 1992, 2002, and 2012, followed by mapping PVR agricultural lands.

Mapping land cover/use

Land cover is the vegetation or other kind of material that covers the land surface. Land use is the purpose of human activity on the land and is usually, but not always, related to land cover. The NRI uses the term land cover/use to identify categories that account for all the non-federal surface area of the United States. For SAF we mapped land cover/use by combining data from the NRI, the USGS National Land Cover Dataset (NLCD) for 2011, and the NRCS Soil Survey Geographic Database (SSURGO) soil database. The resulting SAF land cover/use dataset uses classes consistent with the NRI (Table 2) and introduces three additional land cover/use classes. SAF classes that are consistent with NRI include: cropland, pastureland, rangeland and forest land. The SAF woodland class is a new land cover/use class, which is a subset of the NRI forest land class, and maps the area of forest on farms reported by operators during the Census of Agriculture (CoA) from NASS. SAF adds an additional developed land cover class to map low density residential land use that is not explicitly represented in NRI. SAF also distinguishes within federal lands grazed versus non-grazed federal lands. Note that while NRI defines their classes as "cover/use,", the NLCD defines their classes as "use/cover;" thus," -- so we retain the distinction between cover and use in this report.

To generate the land cover/use maps for 1992, 2002, and 2012, we: (a) defined desired land cover/use types that were consistent with the NRI; (b) generated a suitability surface for each agricultural cover type (cropland, pastureland, grazing, woodland); (c) identified the locations that maximized the suitability values of the land cover types to equal the estimated acres of that agriculture type as estimated in the NRI by county; and (d) merged together data layers into a national dataset. Figure 1 provides a data flow model of the modeling process. Note that we attempted to quantify changes from

1982 forward to 2012, but because many of the datasets used to model land cover/use represent ~1990 conditions, the results were too inconsistent and too variable. Therefore, we chose to evaluate change from 1992 to 2012, rather than from 1982.

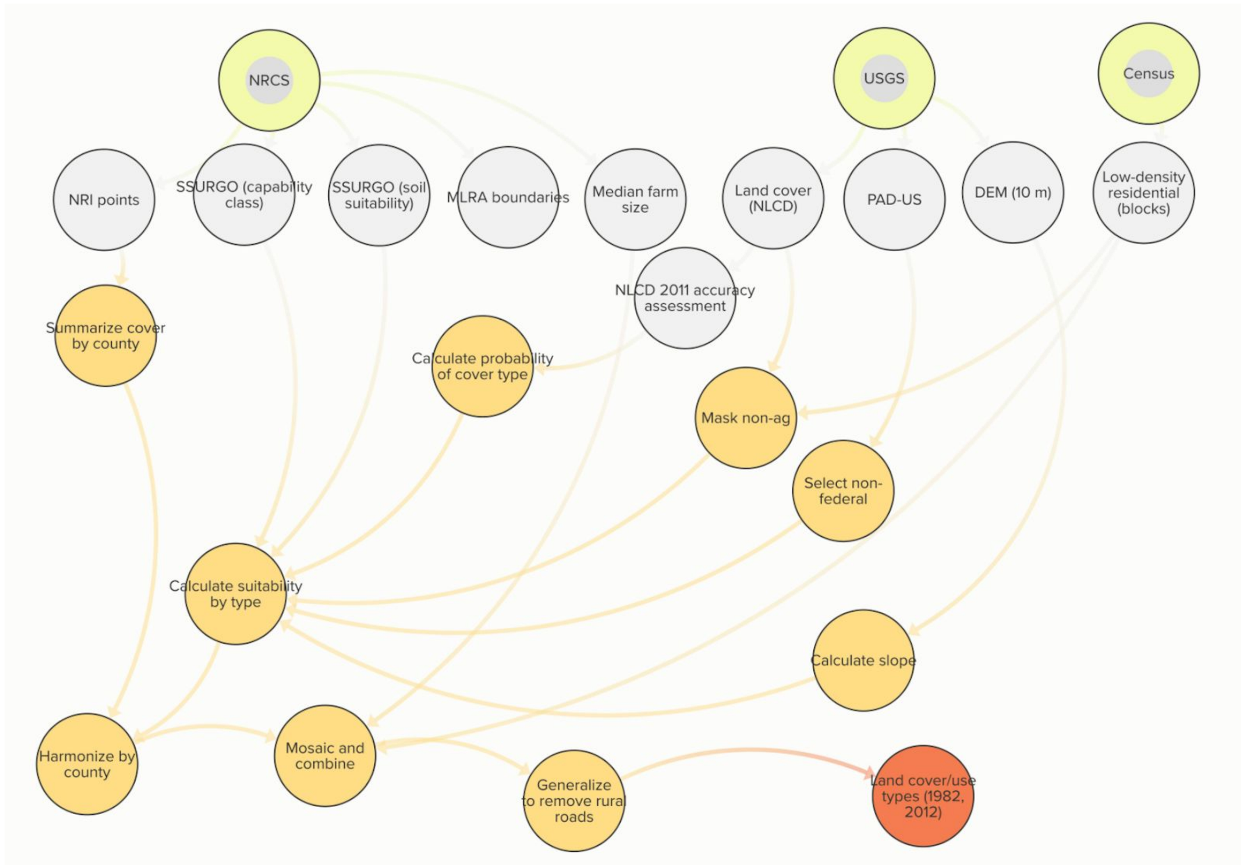

Figure 1. A conceptual flow diagram of the model used to generate land cover/use types, showing agencies, datasets (grey), analytical processes (light orange), and products (orange) of the land cover/use datasets. See Table 1 for additional details about data used in modeling SAF land cover/use and PVR datasets.

Table 1. The name, source, and scale of spatial datasets used in the SAF products.

Name	Source/URL	Scale	Notes
Land use/cover: NLCD 2001, 2011	DOI/USGS National Land Cover Dataset, v3	CONUS, 30 m	An accuracy assessment is available in Wickham et al. 2017.
Land use/cover: NLCD 1992	DOI/USGS National Land Cover Dataset 1992	CONUS, 30 m	Similar but different classes and methods as compared to v3 for 2011-2011, see Table 2
Land cover/use: NRI	USDA/NRCS National Resources Inventory	CONUS, ~800,000 sample points	State summaries are available publicly. We obtained point locations through an agreement with NRCS.
Agricultural cover/use: CDL	USDA/NASS Cropland Data Layer	CONUS, 30 m, spatial confidence layers	Available 2008-2017. Also available through "CropScape" portal
Farm size	USDA/NASS Census	US, county	
Soils: SSURGO	USDA/NRCS Soil Survey Geographic Database	CONUS, polygons, 1:24,000-100,000	SSURGO version October 2017.
Water including lakes/reservoirs and wide streams/rivers: NHDH	DOI/USGS National Hydrography Dataset High Resolution	CONUS, vector, 1:24,000	
Major land resource areas	USDA/NRCS MLRA	CONUS, vector, 1:250,000	V4.2 (2006)
Elevation	DOI/USGS National Elevation Dataset	10 m	
Protected areas for non-federal and federal lands	DOI/USGS Protected Areas Database		v1.4
Housing density	DOC/US Census of Housing	Block-level	Following Theobald (2005)

Table 2. The land cover/use types, definitions, and specific datasets/methods used to map each type. *Denotes new classes mapped by the SAF effort.

Cover/use	SAF class	NRI	Definition
Cropland	1	Cultivated (1), Uncultivated (2)	Areas used for the production of adapted crops for harvest, including cultivated and non-cultivated. Cultivated cropland comprises land in row crops or close-grown crops and also other cultivated cropland, for example, hayland or pastureland that is in a rotation with row or close-grown crops. Non-cultivated cropland includes permanent hayland and horticultural cropland.
Pastureland	2	3	Areas managed primarily for the production of introduced forage plants for livestock grazing. Pastureland cover may consist of a single species in a pure stand, a grass mixture, or a grass-legume mixture, regardless of whether or not it is being grazed by livestock. Management usually consists of cultural treatments: fertilization, weed control, reseeding or renovation, and control of grazing.
Rangeland	3	4	Areas composed principally of native grasses, grasslike plants, forbs or shrubs suitable for grazing and browsing, and introduced forage species that are managed like rangeland.
Forestland	4	5	Areas that are at least 10% stocked by single-stemmed woody species of any size that will be at least 4 meters (13 feet) tall at maturity. The minimum area for classification as forest land is 1 acre, and the area must be at least 100 feet wide.
Woodland*	5	NA	Primarily forested cover that is part of a functioning farm unit. Forested land cover/use that is nearby crop or pastureland (no further than 1 mile).
Urban/built up	6	7	Occupied by urban developed or “developed” areas of commercial, industrial, transportation, and high-density residential. These locations are mapped directly from the urban/developed categories (21-24) from the USGS National Land Cover Dataset (https://www.mrlc.gov/). Typically, residential areas with less than 1 housing unit per 1-2 acres are NOT represented in this class.
Water	7	9 & 10	Covered by freshwater (lakes, reservoirs, large rivers), and includes some near-shore ocean. From National Hydrography Dataset High Resolution waterbodies (ponds, lakes, reservoirs).
Federal	8	11	Federal lands, from USGS Protected Areas Database, v1.4.
Federal (grazed)*	9	NA	Compiled from USFS and BLM allotment data for 2014 and 2015.

Cover/use	SAF class	NRI	Definition
Other	10	6 & 8	Locations that were not classed in other cover/use classes, typically occurring on or along rural roads, or scattered in areas with little vegetation cover such as barren or steeper slopes. This can include CRP.
Low-density residential*	11	NA	Locations dominated by residential land use with low-densities of houses, from 1 unit per ~2 acres and larger lots. Housing density is calculate from US Census block-level housing statistics, and the threshold between low-density residential and agricultural uses is determined for each county by finding the ~10th percentile of farm acreage.
CRP	NA	12	Because Conservation Reserve Program (CRP) locations were not available for SAF spatial modeling efforts and because we could not determine what NLCD classes represented CRP lands, we did not include CRP acreage in the cropland category.

SAF relies primarily on the NLCD as an input source for mapping land cover. Note that because the NLCD for 1992 is generated using a slightly different methodology than the 2001-2011 v3 series, it has slightly different classes which are crosswalked as shown in Table 3.

Also note that because roads are not a separate class in the NLCD, they are represented mostly by low-to-high intensity developed class pixels. We used a filtering procedure on the 2001 and 2011 NLCD v3 datasets to identify smaller, more rural roads (following Theobald 2013; also more recently: Soulard et al. 2018) for two reasons. First, the land represented by a pixel (30 m x 30 m) that overlaps a road typically has only a portion of its area occupied by a road, while the remaining area might have non-developed characteristics. This is especially the case for smaller rural roads that are often only 5-10 m wide, and thus, is over-represented (Lark et al. 2017). Second, roads from 2006 (US Census TIGER 2006) are “burned in” to the dataset so they are static from 2001 and 2011 (and represent 2006 on-the-ground conditions). We used a morphological filter to remove these narrow roads in rural areas by applying a closing and then dilation filter (Theobald 2013) applied in rural areas (defined as being areas other than US Census urban areas), and replaced them with the nearest non-urban cover type. Note that we did not use the “roads-removed” land cover dataset for the suitability surface because that model explicitly accounts for the uncertainty in the mis-classification of cover types along roads. It is challenging to properly represent rural roads because they are much narrower than the resolution of the NLCD dataset (30 m). This scale issue means that land cover types adjacent to rural roads are particularly difficult to map correctly. This is a known issue with Landsat-based mapping products (Theobald 2013; Lark et al. 2017).

Table 3. Reclassed NLCD 1992 values to their equivalent classes in the NLCD 2001-2011 series.

Name	NLCD 1992	NLCD 2001-2011
Water	11	11
Ice/snow	12	12
Developed, open space	85	21
Developed, low-intensity	21	22
Developed, medium-intensity	22	23
Developed, high intensity	23	24
Barren	31	31
Barren	32	31
Barren	33	31
Forest - coniferous	41	41
Forest - deciduous	42	42
Forest - mixed	43	43
Shrubland	51	52
Cropland	61	82
Grassland	71	71
Pastureland	81	81
Cropland	82	82
Cropland	83	82
Cropland	84	82
Woody wetlands	91	90
Herbaceous wetlands	92	95

Generating suitability surfaces

For each agricultural land cover type, *i*, we calculated the suitability of that type for each pixel across the landscape using a combination of factors thought to influence the distribution of a given agricultural land cover/use type (Bonham-Carter 1994; Carr and Zwick 2007). Here we use the term "suitability" to refer to the likelihood that a location is occupied by one of the four agricultural cover types, not a more integrated analysis that includes soil productivity (as is described below). Note that we excluded from consideration for agricultural cover those locations (pixels) that were identified as urban/developed (from NLCD, including open space to high-intensity, classes 21-24), water (from USGS NHD), or snow/ice.

For suitability, S_i (Figure 2), we assumed a resulting land cover/use type *i* (e.g., cropland) would occur preferentially at locations that have:

- productive soils (*c*), where *c* is assigned the reverse order of values from SSURGO non-irrigated land capability classification system (variable "niccdcd");
- evidence from NLCD that at a given location the target cover/use type was there, based on the probability that a given location is a given NLCD class (e.g., cropland, class=82). That is, we use the NLCD uncertainty assessment (Wickham et al. 2017; Table 4) to calculate the probability, *p,* that a pixel is in class *i*;
- flatter slopes (*s*), where *s* is calculated as percent gradient and max-normalized to range from 0 to 1.0; so that $s' = 1-((sqrt(s)) / sqrt(100))$;
- land only, found by excluding water as specified by the USGS National Hydrographic Dataset (NHD) high resolution water bodies (*t*; we elected to not use water class from NLCD because the water class can under-represent reservoir extent because of low-water and because of minor mis-classification errors);
- non-federal lands (*f, f=1* for non-federal, 0 for federal); and
- cropland type in any of the years from 2008-2011 in the CDL (*d*) (only for crop land cover/use type). This was filtered using a 90-m radius (3x3) window of erosion and dilation.

We calculated suitability of type *i* as:

$$S_i = c * p * s' * t * f * d.$$

Note that we calculated *p* for each class *i* to explicitly incorporate the uncertainty of the NLCD use/cover classification, which has an overall accuracy of 76%. Although the accuracy of the NLCD for cropland is 83%, it is only 48% for pastureland, and 63% for all developed classes. We incorporated the uncertainty of classification into the calculation of suitability to include the errors likelihood in a given pixel (Table 4).

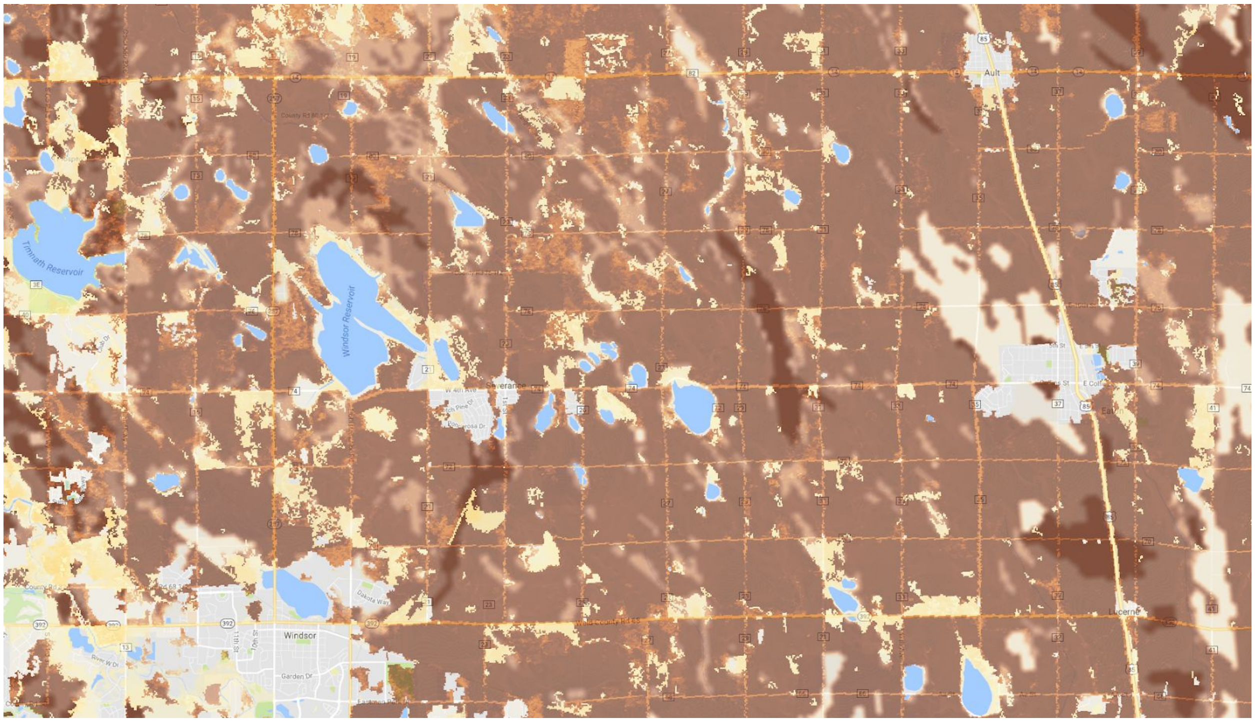

Figure 2. A map of the suitability surface for cropland, near Windsor, Colorado ([40.52 lat, -104.88 lon]). Dark brown areas show higher suitability for cropland, yellow is lower/unsuitable. Urban/developed areas, federal, and water areas are excluded from the suitability surface (shown in white, grey, and blue). Rural roads follow the boundaries of 1-mile sections.

Table 4. Listing of National Land Cover Dataset 2011 v3 class types. Note that the probability, *p*, of an NLCD class was calculated using the 2011 NLCD accuracy assessment (Wickham et al. 2017). We applied these 2011 probabilities to the 1992 suitability surface for computational simplicity due to the cross-walking of cover classes, although an accuracy assessment for 1992 does exist (Stehman et al. 2003). For example, a pixel that is classed as Cropland is correct 83% of the time (see italicized value in column "Crop p" and row "82", NLCD class=Cropland. However, a pixel classed as Pastureland has an 8.6% chance that it is "actually" Cropland, and the other rows provide the probability that that cover type is actually cropland. So, for each of the four agricultural types, a data layer is generated where land cover types are replaced with the chance (probability) that pixel *i* is actually type *c*.

NLCD class	NLCD class	Crop *p*	Pasture *p*	Range *p*	Forest & Woodland *p*
11	Water	0.0008	0.0011	0.0002	0.0004
12	Ice/snow	0.0	0.0	0.0002	0.0
21	Developed, open-space	0.0205	0.0411	0.0091	0.0155
22	Developed, low-intensity	0.0017	0.0033	0.0007	0.0004
23	Developed, medium-intensity	0.0	0.0	0.0	0.0002
24	Developed, high-intensity	0.0	0.0003	0.0	0.0
31	Barren	0.0005	0.0006	0.0168	0.0006
41	Forest - coniferous	0.0118	0.0058	0.0101	*0.3665*
42	Forest - deciduous	0.0009	0.0032	0.0440	*0.3176*
43	Forest - mixed	0.0	0.0014	0.0028	*0.1365*
52	Shrubland	0.0055	0.0367	*0.4851*	0.0638
71	Grassland	0.0390	0.2121	*0.3889*	0.0241
81	Pastureland	0.0865	*0.4848*	0.0154	0.0175
82	Cropland	*0.8300*	0.2013	0.0150	0.0145
90	Wetland - woody	0.0021	0.0016	0.0065	0.0405
95	Wetland - herbaceous	0.0008	0.0077	0.0051	0.0019

Harmonizing agriculture lands to NRI estimate

The agricultural land cover/use suitability surfaces were then used in a harmonization process to identify locations to allocate pixels of a given cover type *i* by sorting the suitability values in a county, then start at the pixel with the maximum suitability value *s*, find the pixel with the next lower value, etc., until the number of pixels is equivalent to the area estimated by NRI was attained. Harmonization to the estimated area specified by the NRI was done for each of the four types of agricultural lands (cropland, pastureland, rangeland, and woodland). That is, for each county, we obtained the estimated area of each cover/use type by summarizing the NRCS NRI data points from the years 1992, 2002, and 2012 for four NRI cover/use types (cropland -- both cultivated and non-cultivated, pastureland, rangeland, and forestland). We adjusted a county shapefile to be in concordance with the county-frame used by the NRI dataset, which excludes more recently created counties since 2010 (e.g., Broomfield, Colorado) and combines other small counties into adjacent units (e.g., towns in Virginia), to match the aggregation units used by the NRI.

That is, we sorted all the suitability values in a given county from smallest to largest to obtain the distribution of suitability values (i.e., an empirical distribution function), and plotted this distribution with the suitability surface values on the y-axis and the area (count of pixels) of the non-federal proportion of a county for cover type *i* is plotted on the x-axis. We then find the point on the plotted line where the percent of the county area matches the area estimated in the NRI dataset for that county (where a vertical line intersects the x-axis that matches the proportion of the county). We then find the suitability value where a horizontal line from the point intersects the y-axis.

We first mapped the locations of cropland cover/use type for each county, and then excluded cropland cells in the next step when harmonizing for pastureland cover/use class, following the economic assumption of highest best use (e.g., von Thunen/Alonso Rent Theory; Alonso 1964). We progressed incrementally, where both cropland and pastureland were excluded from harmonizing rangeland, and finally crop, pasture, and rangeland were excluded from the forestland map. To calculate the woodland cover/use type (classified as forest cover but proximal to crop and/or pasture lands, as part of a functioning farm unit, particularly in the eastern US), we obtained the estimated area of woodland acres from the CoA (2012) at the county level. We then calculated proximity of woodlands to crop/pasturelands using cost-distance methods and a suitability surface that favored flatter forested lands adjacent to crop and pasture lands, until the target number of woodland acres for each county was obtained.

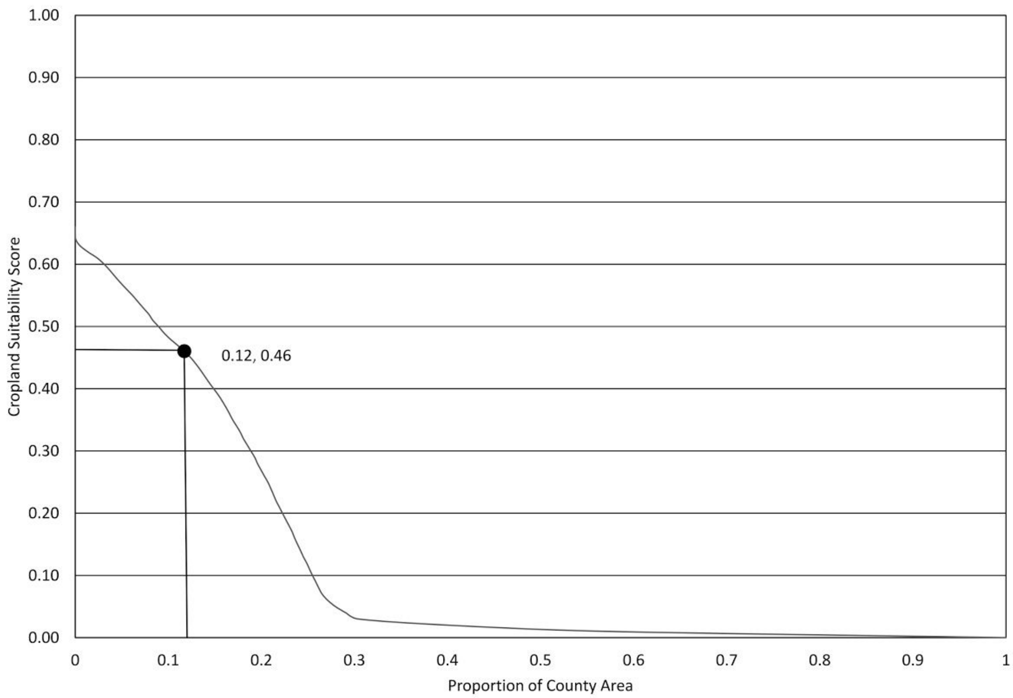

Figure 3. A graph of the cumulative distribution of cropland suitability values for Larimer County, Colorado. The y-axis shows the suitability score, which ranges potentially from 0.0 to 1.0 (0.65 realized in this case, where higher values indicate higher suitability). The x-axis shows the cumulative area associated with declining suitability values, in terms of the proportion of non-federal land area in the county. The algorithm identifies the suitability threshold value that generates the proportion of area specified by the NRI county estimate (here, 0.117 or 11.7%). The pixel locations that have suitability values of at least 0.46 are then re-classed as cropland.

After generating the agricultural layers representing agricultural cover/use types, we then merged this layer of agricultural classes with the NLCD and housing density layers to calculate additional, non-agricultural cover/use types.

Mapping low-density residential

Typically, NLCD developed classes under-represent suburban and exurban residential land use beyond the urban fringe (Theobald 2001; Irwin and Bockstael 2007). We calculated the mean housing density for each of the four developed classes, as well as the proportion of the NRI points identified as urban (including both the “large-urban and “small-urban” classes).

To identify a meaningful housing density threshold to distinguish low-density residential development as distinct from similar housing densities associated with agricultural uses, we evaluated the median farm size at the county level from the CoA for 2012 as a refinement to region-wide assumptions about the threshold at which farms and ranches are too small to provide an efficient production capacity (these are often called “subsidized farms” or “hobby farms”). Using county level farm size data for defining low-density residential land use takes into account the range in median farm size as it varies across the continental US., with larger farms in the Midwest (>160 acres) and smaller farms on the east and west coasts (roughly 10 acres), an improvement over simply assuming this threshold was at 40 acres in the West and 10 acres in the East (Sorensen et al. 1997, 2002; Bierwagen et al. 2010). To further refine this threshold because the distribution of farm sizes typically is skewed to smaller farms, we obtained *quartiles* of county farm size from the CoA for 2012 (NASS 2017). We then estimated, through discussions and visual evaluation of the thresholds viewed on top of high-resolution aerial photography by regional experts across the country, that low-density residential land would occur at half the acreage of the lowest quartile (12.5%) farm size for each county. We identified the low-end of the tail of the distribution of farm size (approximately the 10th percentile), below which we considered agricultural lands (cropland, pastureland, rangeland, and woodland) to be effectively removed from the agricultural land base and be reclassified as low-density residential (Figure 4). Figure 5 shows the distribution of the threshold values for all counties.

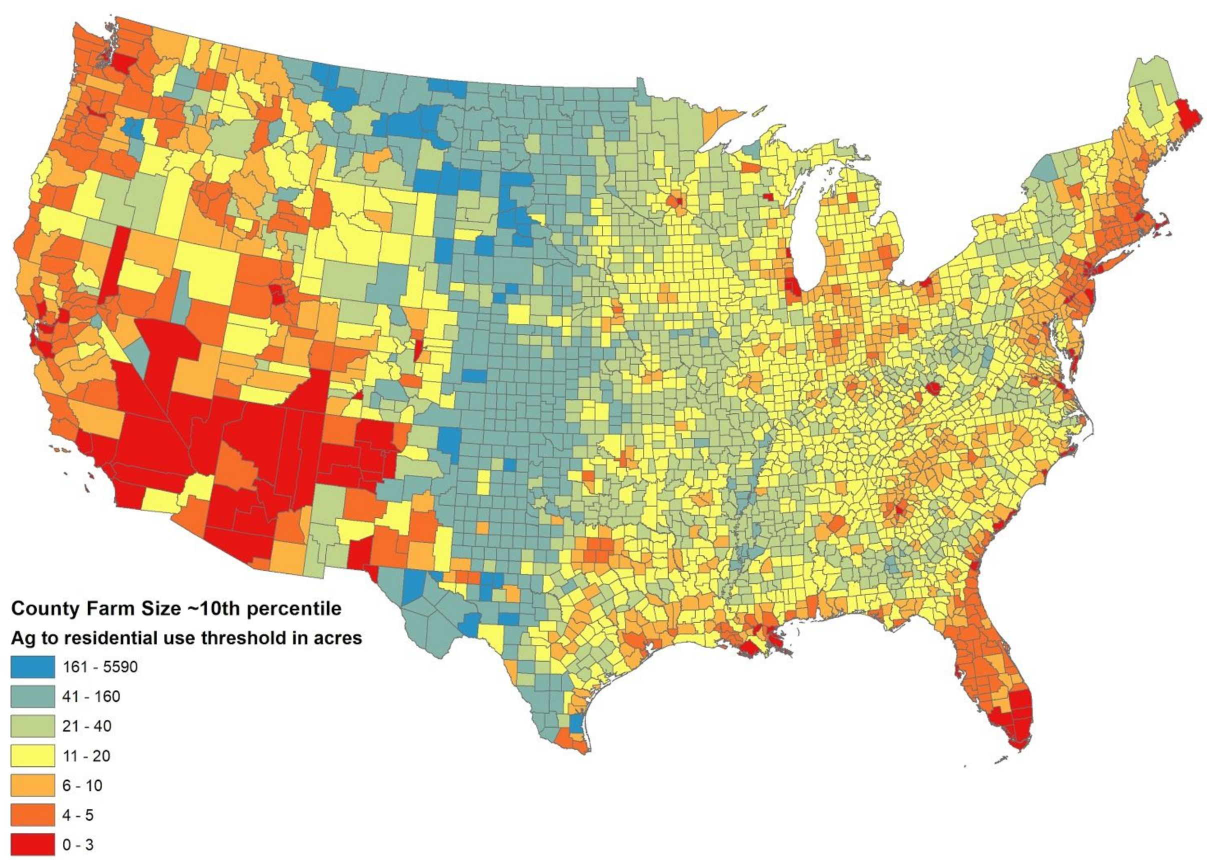

Figure 4. Agriculture to residential use threshold, based on ~10th percentile of farm size for 2012 at the county level. Note the maximum acreage threshold was set to 1,000 acres.

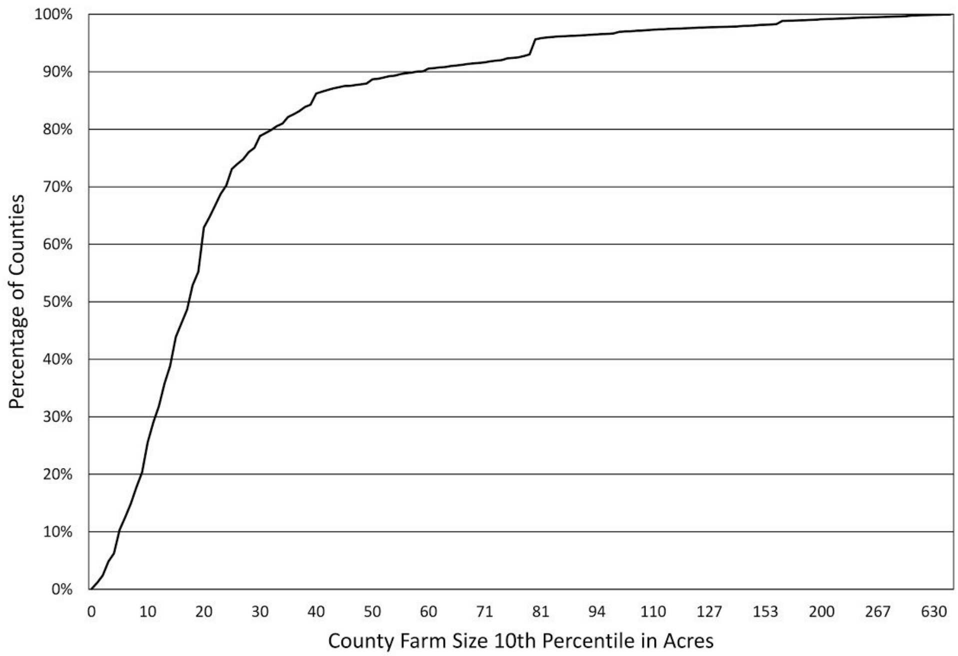

Figure 5. The cumulative distribution of the 10th percentile of farm size for each county for 2012, which was used as the threshold between low-density residential and agricultural land use (in acres).

Productive, versatile, and resilient agricultural lands

We generated a map that represents the potential of agricultural lands based on a location's productivity, versatility and resiliency (PVR), circa 2012. Although this is a snapshot in time, the long-term sustainability of keeping the land in cultivation or in other agricultural uses in general depends on the PVR values of the land base. *Productivity* is defined typically as output per unit of input (often measured as crop yield per acre). The highest productivity occurs in coastal areas where climate, soil, location and irrigated conditions favor the production of perishable crops (fruits and vegetables), where multiple crop cycles are supported (e.g., southern latitudes), or where integrated livestock operations draw from an extended cropping area. Unfortunately, productivity can often mask environmental or health components of soil quality (Osteen et al. 2012). *Versatility* is the ability of land to support production and management of a wide range of crops. It is mainly assessed in terms of soil and land physical characteristics (Bloomer 2011). *Resiliency* is the land's ability to maintain its potential to provide ecosystem services and depends on the same factors that determine potential productivity (topography, relatively static soil properties and climate; Herrick et al. 2016). The PVR analysis considers soils, their limitations, climate, type of production and whether the land was capable of producing commonly cultivated crops and pasture plants without deterioration over a long period of time.

To identify the characteristics, the indicators, and weighting amongst these factors, we used a formal elicitation process using established methods (Speirs-Bridge et al. 2010; McBride et al. 2012) and gathered parameters and estimates from 33 agricultural experts with a variety of experience and from around the country. We generated the PVR values using three factors (*f*): 1) soil productivity, 2) land cover/use, and 3) food production capability. Figure 6 provides a conceptual model of the process we followed. The experts participated in a structured process based on decision analysis theory (following Saaty 2008; Roszkowska 2013) to identify the relative importance or weight (*w*) of a PVR factor by assigning a numerical weight to each component within each PVR factor (see SI x for a review of the elicitation process). The resulting PVR map assigned a 0 to 1.0 value based on its potential, where:

$$PVR = f_1w_1 + f_2w_2 + f_3w_3 .$$

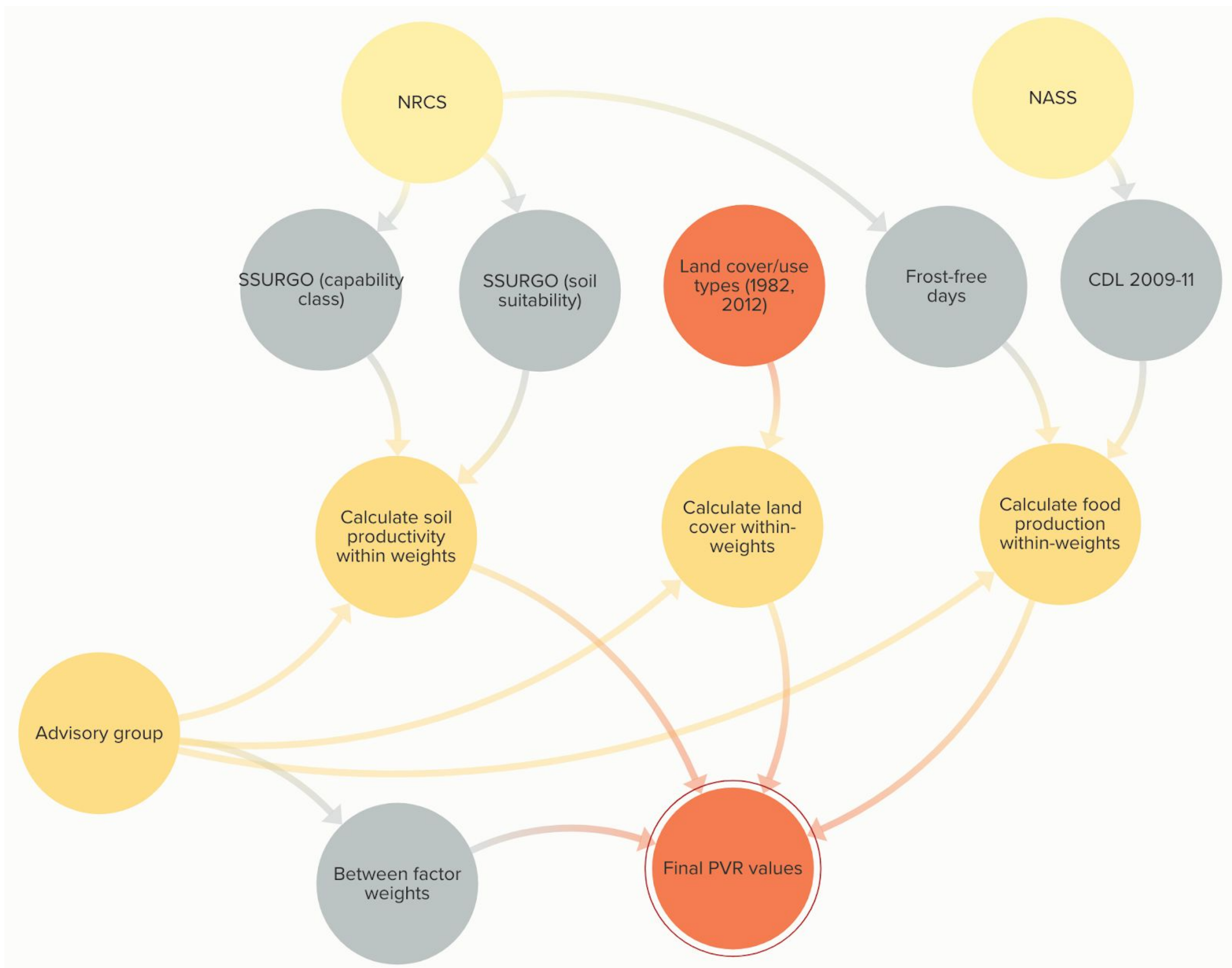

Figure 6. A conceptual flow chart of the model used to generate a map of productive, versatile, and resilient agricultural lands.

Modeling soil productivity

To generate the soil productivity factor we used data on important farmland designations and land capability classes from the SSURGO. The soil productivity factor measures the capacity of soils to support agricultural production but also provides information about the land's versatility and ability to provide production with varying weather conditions (e.g., precipitation, temperature regimes). Using the attribute "farmland class" from SSURGO we distinguished prime farmland, prime farmland with limitations, unique farmland, farmland of statewide importance and farmland of statewide importance with limitations. Based on discussions with our advisory group and state soil scientists, we reclassified locally important soils in all states as not prime except Michigan and Ohio because states inconsistently define their locally important soils and most states identify fewer than 1,000 acres as locally important. In Michigan, we reclassified locally important soils in counties adjacent to Lake Michigan as unique (since these areas support fruit trees or vineyards) and reclassified the locally important soils in remaining counties as statewide important. In Ohio, we reclassified locally important soils as statewide important. We estimated that the following types were in order of importance: prime, unique, prime with imitations, state important and state important with limitations. Soil productivity within-weight values were estimated using the advisory group rankings, converted using the square root of the rank sum weight (Roszkowska 2013).

We then strengthened the analysis by factoring in production limitations identified in USDA NRCS non-irrigated land capability classes (see Table 5; M. Robotham, *pers. comm*.). Also note that a small extent (~2%) of non-federal lands have not been mapped in the SSURGO dataset, we assigned an average within-weight value for these areas. The resulting soil productivity within-weights (f_1) were calculated from the product values in Table 5.

To further strengthen the soil suitability analysis, we included a secondary factor based on production limitations documented within USDA NRCS Land Capability Classes (LCC) (USDA SCS 1961). The USDA developed this classification to group soils primarily on the basis of their capability to produce commonly cultivated crops and pasture plants without deteriorating over a long period. The LCC takes into account management hazards (e.g., erosion and runoff, excess water, root zone limitations and climatic limitations). It also helps identify production versatility, identifying whether soils can be used for cultivated crops, pasture, range, woodland and/or wildlife food and cover. The LCC identifies eight categories with increasing limitations. Land in Classes I through IV is suited to cultivation although Classes II through IV have increasing limitations that reduce the choice of plants and require the use of progressively more conservation practices. Classes V through VIII are not suited to cultivation and their use is limited largely to pastureland, rangeland, woodland or wildlife food and cover. To improve the food production factor, the analysis also incorporated information about growing season length that limits production in parts of the country but allows almost year-around production in some of the southern states and in some coastal regions.

Table 5. Within-weights calculated as a function of soil productivity (from farmland class) and non-irrigated land capacity class, calculated as the product of the two variables: productivity and capacity class (red = higher soil productivity, blue = lower productivity). Within-weights were calculated by using the rank-sum weight (Roszkowska 2013). Weights were generated from ranks elicited from experts in response to how importance of each productivity class was in identifying valuable agricultural land.

		Land Capability limitation classes	few	some	severe	very severe	little erosion/limit.	severe	very severe	very very severe
		Ranking	1	2	3	4	2	3	4	8
Productivity class name	Ranking	Within-weights	1.00	0.87	0.71	0.50	0.87	0.71	0.50	0.00
Prime	1	1.00	1.00	0.87	0.71	0.50	0.87	0.71	0.50	0.50
Unique	2	0.72	0.72	0.62	0.51	0.36	0.62	0.51	0.36	0.36
Prime lim	3	0.55	0.55	0.48	0.39	0.28	0.48	0.39	0.28	0.28
State	4	0.50	0.50	0.44	0.36	0.25	0.44	0.36	0.25	0.25
State lim	5	0.30	0.30	0.26	0.21	0.15	0.26	0.21	0.15	0.15
Local	6	0.10	0.10	0.09	0.07	0.05	0.09	0.07	0.05	0.05
Not prime	7	0.10	0.10	0.09	0.07	0.05	0.09	0.07	0.05	0.05

Modeling infrastructure

A second factor in the PVR map represented a surrogate for the infrastructure and ability of an area to support different types of agricultural production. Land cover that remains in agriculture consistently through time indicates there may be relatively fewer limitations and environmental consequences since the land remains in production. For each of the SAF agricultural classes, the advisory panel estimated the ranks, which we then converted as rank sum weight (*f2*; Table 6; Roszkowska 2013).

Table 6. Listing of the within-weight values (f_2) associated with SAF classes estimated for the land cover/use factor of the PVR analysis. Weights were generated from ranks elicited from experts in response to how important cover/use classes were in identifying valuable agricultural land.

SAF Class	Within-weight
Cropland	1.00
Pastureland	0.54
Rangeland	0.32
Woodland	0.25

Modeling food production

The food production factor characterizes the versatility and uniqueness of a location. Versatility can be deduced from the type of crop being grown as well as the length of the growing season. We grouped the crop types listed in the CDL, for 2008 through 2012, into one of five classes: 1. fruit and nut trees; 2. fruits and vegetables grown as row crops; 3. staple food crops (e.g. wheat, rice, barley, oats, dry beans, potatoes); 4. feed grains, forages and crops grown for livestock feed and processed foods (corn and soybean; hay and alfalfa; oilseeds and sugar beets and sugarcane); and 5. non-food crops (i.e., crops used for energy production excluding corn, fiber, tobacco and nursery/greenhouse). To calculate the within-weights for this factor, we elicited rankings of these five classes from our advisory group and then converted them to weights using rank sum weight (Roszkowska 2013). After calculating the within-weights and upon inspecting the resulting maps, the mapping team recommended a greater distinction or separation in values, so we applied a squared transform to accentuate the differences between the weights of the high and low ranked classes (Table 7). To account for the inter-annual variability of crop types from 2008-2012, we calculated the average class rank over the five years for each pixel.

We also included information about growing season length to account for obvious regional differences in production value that varies especially because of climate (e.g., multi-rotations per year in California and Florida vs. short summer season in Maine). To do this, we adjusted the within-weight values of food production using a rough surrogate for the length of the growing season that is linked to general soil patterns. That is, we multiplied the food production weights by the proportion of freeze-free days in year, for each major land resource area (MLRA). We then normalized the overall food production value by the 90th percentile value (0.17) to stretch the within-weight values (f_3) to 0 to 1.0.

Table 7. Listing of the within-weight values associated with food production classes estimated by the advisory group. Weights were generated from ranks elicited from experts in response to the importance of each class in identifying valuable agricultural land.

Food production class	Final within-weight
Fruit & nut trees	1.00
Fruits and vegetables	0.96
Staple	0.63
Feed	0.33
Non-food	0.09

Overall PVR calculation

We calculated the overall PVR values as:

$$PVR = f_1 w_1 * f_2 w_2 * f_3 w_3$$

where *w* values were the between-weights estimated by the advisory group that summed to a value of 1.0 (w_1=0.541; w_2=0.196; w_3=0.314).

Agricultural lands with lower PVR values have progressively greater limitations and usually require more inputs although farmers can and do farm these lands by adapting crops and practices. Conversely, areas with higher PVR values are extremely valuable because they have few current and long-term limitations to agricultural production. To simplify the gradient values in the PVR dataset, we identified the PVR value of land could support *intensive food and crop production*, typically associated with increased mechanization and high-value crops. This threshold was identified by finding the minimum values of each of the three factors that were sufficient to meet this level. That is, we included: soil productivity types of prime, prime with limitations and unique; land cover/use cropland and pastureland types; and all food production types except the non-food type.

Results

Land cover/use patterns and statistics

We found that of the major land cover/use types, agricultural dominates the continental US landscape (Table 8). In 2012, agricultural lands occurred on over 911M ac of non-federal land, with an additional 158M ac of grazing on federal lands, for a total of over 1,070M ac (Figures 7 & 8). The largest proportion of the agricultural land in 2012 was rangeland (38.2%, with an additional 14.9% for grazing on federal land), followed by cropland (29.3%), pastureland (10.1%), and woodland (7.5%). We also found that urban and low-density residential land cover/uses combined occupy 141M ac (7.3% of the US). For 1992, we found that agriculture occupied more land -- over 959M ac (1,117M ac including federal grazing lands).

Table 8. Agricultural lands and federal lands used for livestock grazing for the continental US. Non-federal agriculture cover/use classes include cropland, pastureland, rangeland, and woodland.

	1992		2012	
Land cover/use class	**Thousands of acres**	**% of the US**	**Thousands of acres**	**% of the US**
Cropland	341,353	17.6	313,845	16.2
Pastureland	136,434	7.0	108,410	5.6
Rangeland	422,291	21.8	409,275	21.1
Forest	369,666	19.1	328,572	17.0
Woodland	59,032	3.0	80,136	4.1
Urban	40,576	2.1	71,464	3.7
Water	43,744	2.3	43,469	2.2
Federal	217,935	11.2	217,934	11.2
Federal (grazed)	158,418	8.2	158,418	8.2
Other	75,004	3.9	87,889	4.5
Low-density res.	62,329	3.2	69,536	3.6
Unknown		0.6		2.5
Total	1,937,713	100.0	1,937,713	100.0
Non-federal agriculture	959,110	49.5	911,666	47.0
Agriculture (non-fed and federal grazed)	1,117,528	57.7	1,070,084	55.2
All federal lands	376,352	19.4	376,352	19.4
Developed (urban & low-density)	102,904	5.3	141,000	7.3

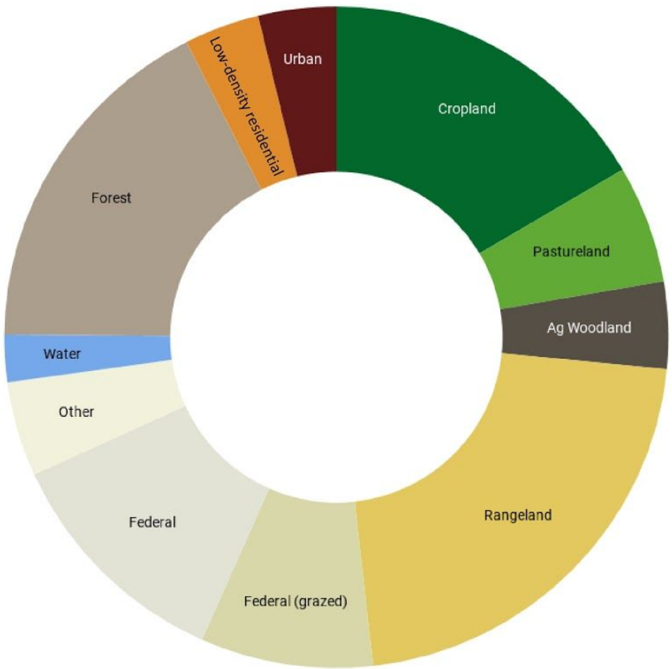

Figure 7. The proportion of land cover/use types in the continental US in 2012.

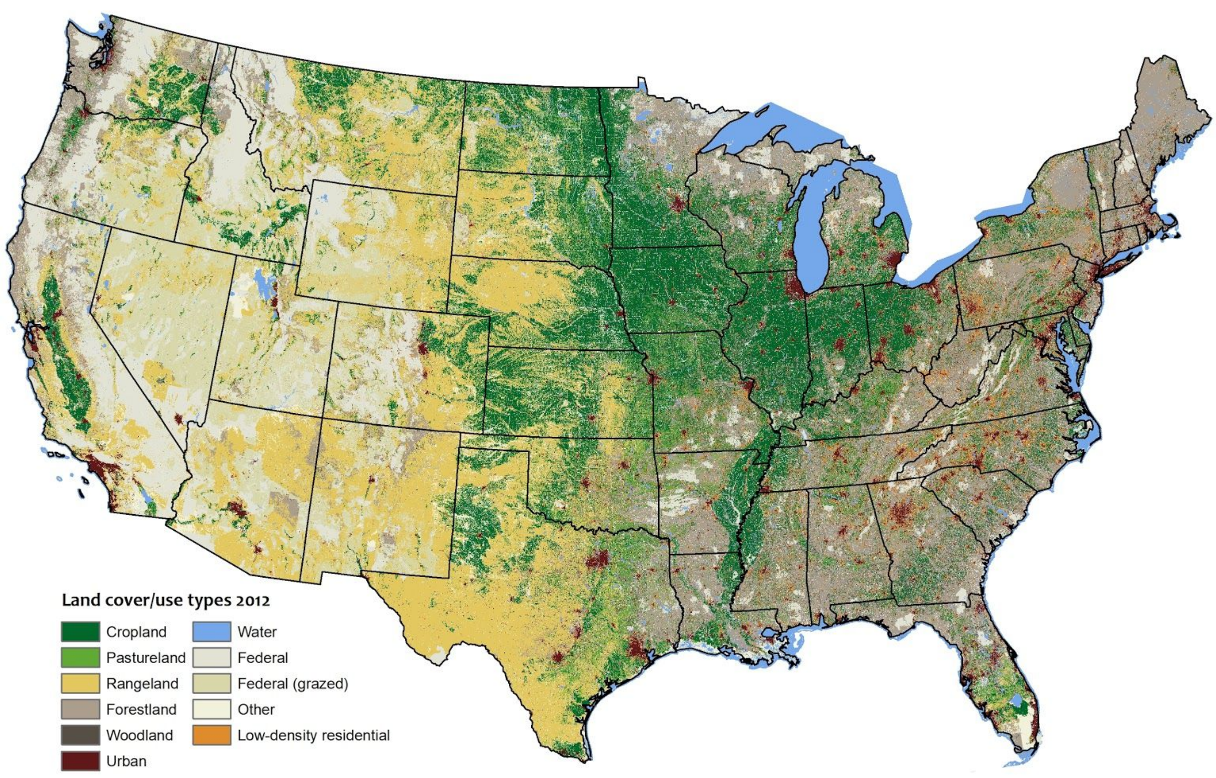

Figure 8. The land cover/use types identified for 2012 in the continental US.

We found an overall net loss of agricultural lands from 1992 to 2012, with over 27M ac of cropland, 28M ac of pastureland, and 41M ac of rangeland lost, though woodland expanded from 59 to 80M ac. Also, developed lands expanded, with urban cover/use increasing from over 40 to 71M ac, and low-density residential expanded from 62 to 69M ac. We found that over 62% of the newly developed lands occured on lands that were agricultural cover/uses in 1992. About 18M ac of agricultural lands (59% of conversion) occurred through urban development, while low-density residential development converted nearly 13M ac of agricultural lands (41% of conversion).

Important agricultural lands

As expected, we found that the PVR values of agricultural lands strongly varies across the US (Figure 9), and that the majority land with high PVR values occur in the Midwest, especially in Iowa, Illinois, and Indiana, as well as portions of Kansas, Minnesota, Nebraska, Ohio, and the Dakotas. In the West, the Columbia Plateau, Willamette Valley in Oregon, and central valley of California had sparser but significant regions of agricultural lands with high PVR values.

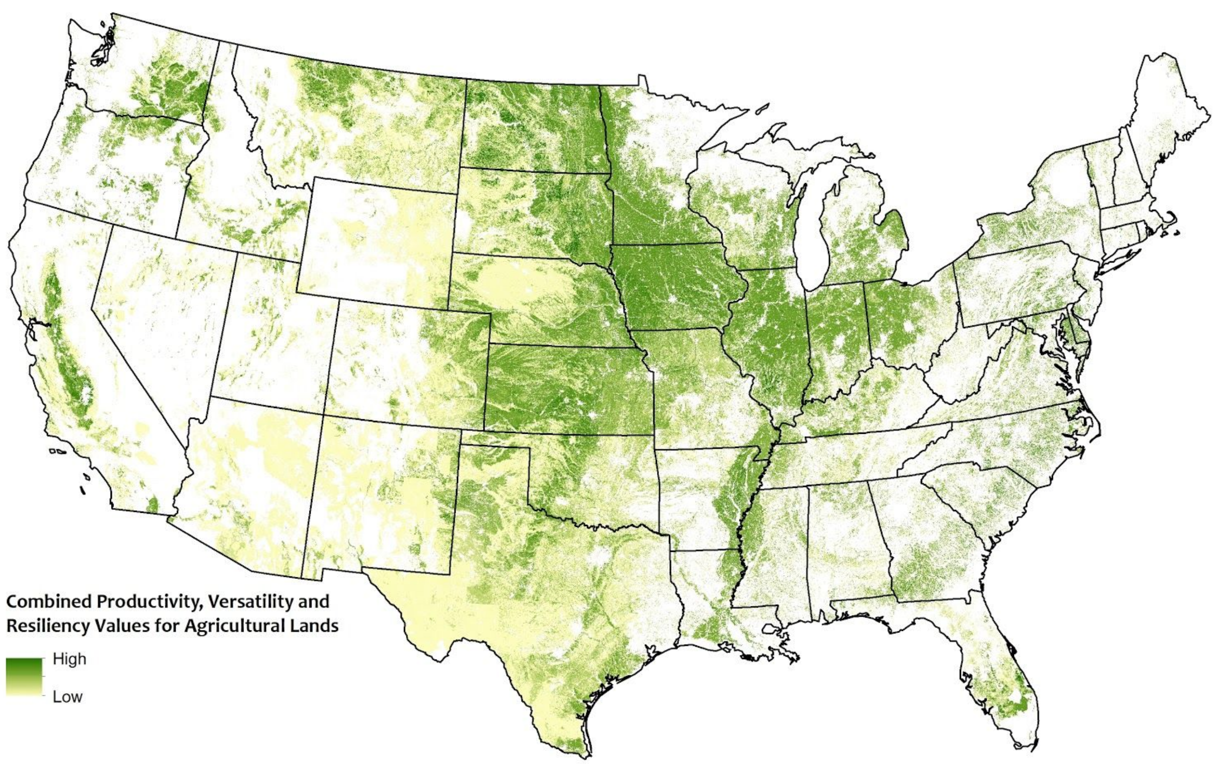

Figure 9. The productive, versatile, and resilient values for agricultural lands in the continental US. Non-agricultural lands are shown in white, and include urban areas, federal lands, and water bodies. Note that many high value PVR lands are found locally, and nearly all states have at least pockets of above-average PVR values, but this is difficult to see because of the national extent of this map.

Figure 10 shows the statistical distribution of PVR values, with an overall mean value of about 0.39. The top 25% of the PVR values have a surge in their values, showing a slight non-linearity. We also found that the areas of agriculture that were developed by 2012 had substantially higher PVR values than those that were not converted. That is, most higher-valued PVR lands had a disproportionate amount of conversion due to development. However, for lands with PVR values in the top 25% (>0.51), the pattern of disproportionately high PVR lands converted does not occur.

To help put the PVR value continuum into context with other schemes to measure productivity and importance of agricultural lands, we found the PVR value at each of the NRI points that were designated as prime farmland. We calculated the mean PVR value, which was 0.45. We also compared the PVR values to the SSURGO land capability class designations (using non-irrigated values). The mean PVR value for each of the LCC Class I-VIII, in order, was 0.53, 0.49, 0.40, 0.29, 0.29, 0.20, 0.15, and 0.15. We found that these values correspond well with our use of a threshold value of 0.43 that corresponds with intensive food and crop production. In other words, the intensive food and crop production designation in SAF picked up all of the prime farmland identified by the NRI points, as well as the agricultural land in LCC Classes I and II and some of the agricultural land in LCC Class III.

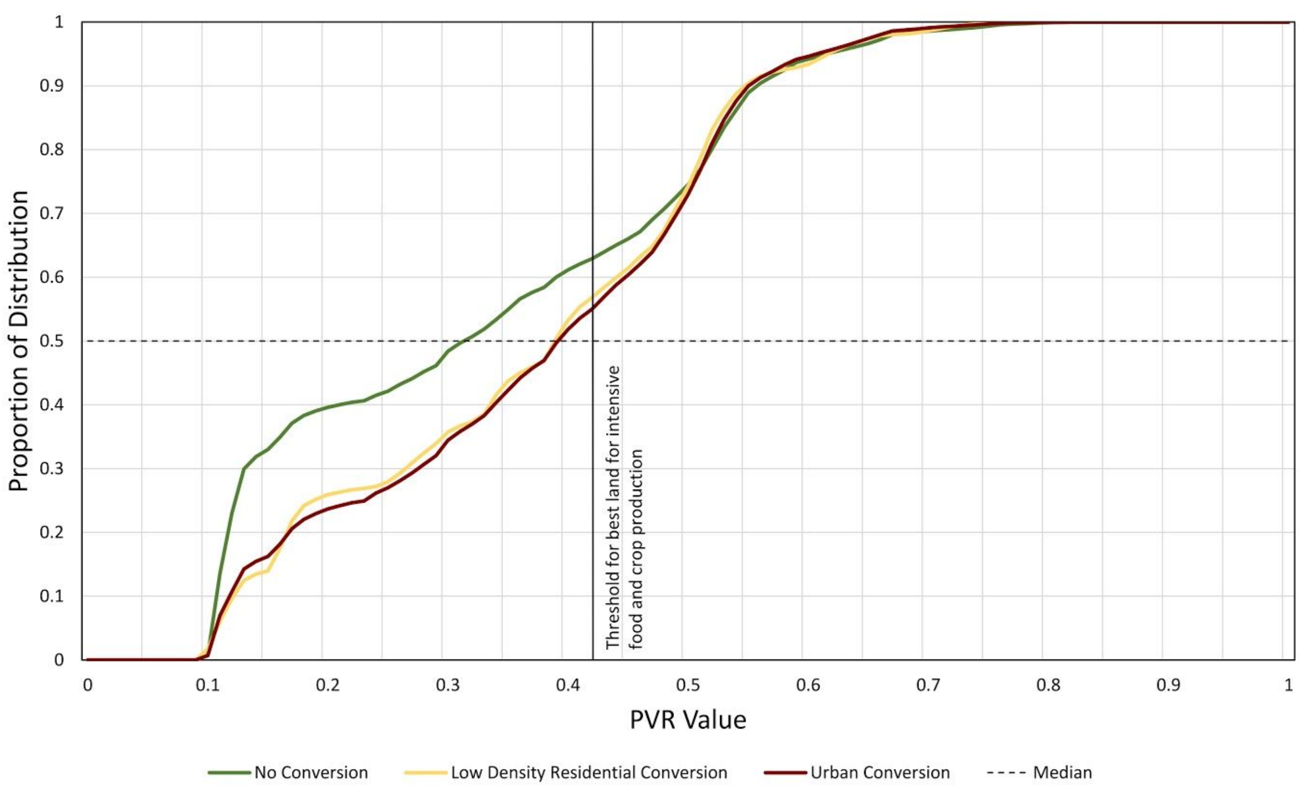

Figure 10. The cumulative distribution function of the productive, versatile, and resilient values for agricultural lands, showing the PVR values on the x-axis and the proportion of the continental US on the y-axis. Three classes are distinguished -- those locations that did not change from 1992-2012, those that were converted to low-density residential, and those that converted to urban land cover/use.

Land cover/use change and conversion of agricultural lands

We show in Table 9 the conversion of agricultural lands to urban or low-density residential land use, and a map of converted agricultural lands (Figure 12). We also provide a cross-tab of area associated with land cover/use types in 1992 against 2012 (Table 10).

Table 9. Conversion by land cover/use types by urban and low-density residential development in millions of acres (M ac), from 1992 to 2012.

Land cover/use		Converted to urban development			Converted to low density residential			Total (urban and low-density) developed		
Type	**% ag lands**	**Area (mac)**	**%**	**% ag type**	**Area (mac)**	**%**	**% ag type**	**Area (mac)**	**%**	**% of ag type**
Cropland	34.3	7.40	28.9	41.0	4.38	18.5	34.5	11.79	23.9	38.4
Pastureland	11.9	4.66	18.2	25.9	4.37	18.5	34.5	9.04	18.3	29.4
Rangeland	44.9	4.28	16.7	23.8	1.40	5.9	11.1	5.69	11.5	18.5
Woodland	8.8	1.67	6.5	9.3	2.52	10.6	19.9	4.20	8.5	13.7
Total ag		18.02	70.4	100.0	12.69	53.5	100.0	30.72	62.3	100.0
Forestland		5.10	19.9		9.73	41.0		14.84	30.1	
Other		2.46	9.6		1.29	5.5		3.76	7.6	
Total		*25.60*	100.0		*23.73*	100.0		*49.33*	100.0	

Table 10. A cross-tab showing area (millions of acres) of conversion from land cover/use types in 1992 (rows) to 2012 (columns). The diagonal cells show the area of land that existed in 1992, and remains in 2012. For example, 238.32M ac remained in cropland.

	2012								
Land Cover Class (1992 rows)	**Crop-land**	**Pasture-land**	**Range-land**	**Forest-land**	**Wood-land**	**Urban**	**Water**	**Other**	**Low-density residential**
Cropland	**238.32**	28.68	26.88	7.51	8.59	7.41	0.87	7.19	4.38
Pastureland	35.15	**49.79**	11.69	9.62	10.14	4.66	0.37	4.96	4.38
Rangeland	22.95	11.38	**341.16**	13.04	4.09	4.29	0.55	17.40	1.41
Forestland	6.18	9.79	11.79	**264.70**	34.18	5.20	1.12	19.74	9.89
Woodland	5.19	5.22	1.56	18.36	**18.91**	1.67	0.28	3.38	2.53
Urban	0.76	0.58	0.48	0.88	0.32	**32.43**	0.09	0.84	2.87
Water	0.36	0.23	0.47	1.08	0.43	0.27	**38.53**	2.06	0.21
Other	4.56	2.60	15.08	12.94	3.35	2.48	1.46	**29.85**	1.31
Low-density residential	0.39	0.14	0.17	0.43	0.12	13.06	0.19	2.47	**42.56**

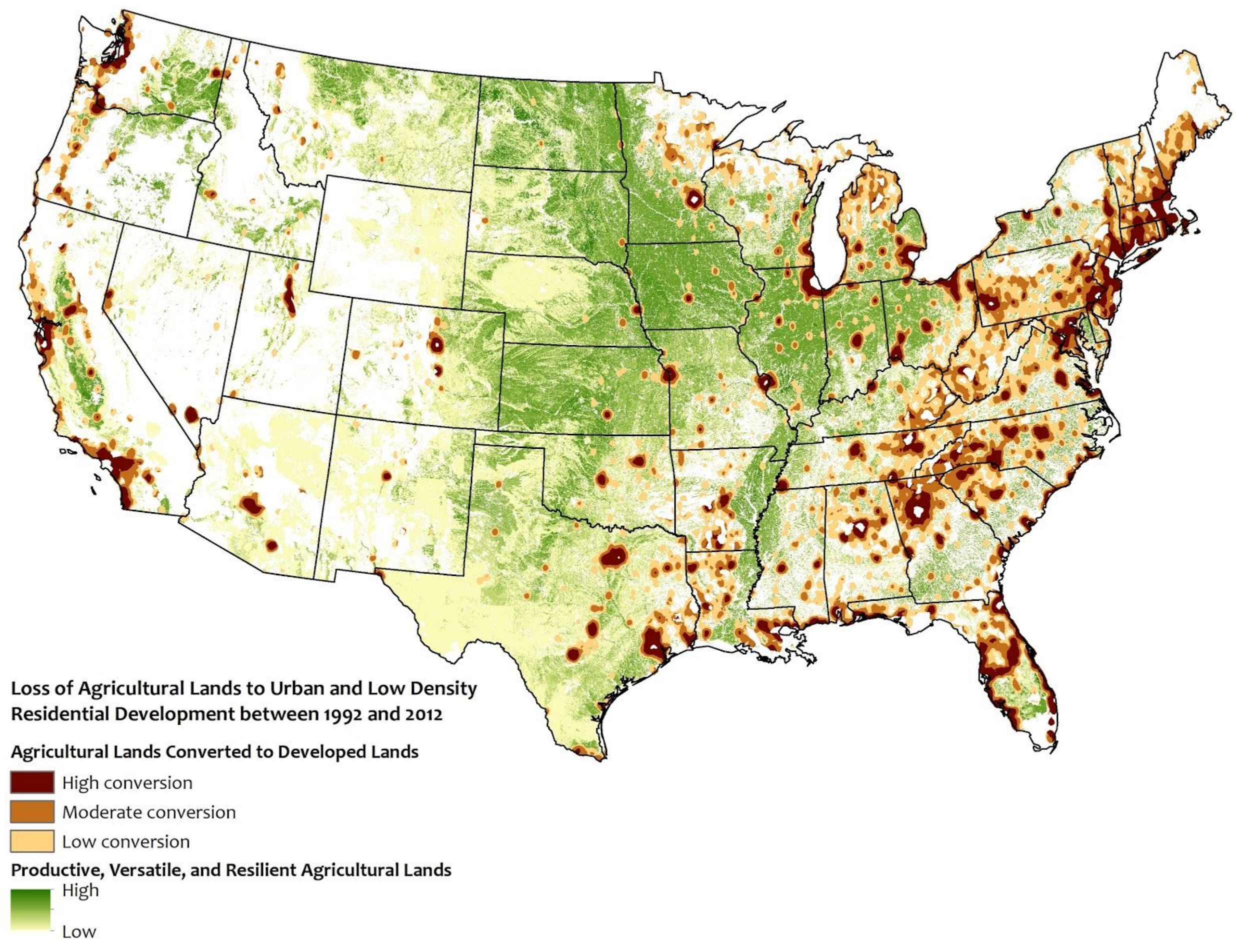

Figure 12. Areas converted from agriculture to developed (urban and low-density residential) land uses from 1992 to 2012 in the continental US in relationship to the areas of productive, versatile, and resilient values of agricultural lands (shown in yellow-green). The metropolitan areas and their expansion are clearly visible as red and orange rings, with lower amounts of conversion in areas beyond the urban fringe. We estimated conversion within a 10-km radius and represented the gradient of agricultural conversion using three classes: low (5 to 10%), moderate (10 to 25% conversion), and high (> 25% conversion).

Comparison and validation of SAF land cover/use maps

Although the SAF land cover/use dataset we developed differs from the NRI in fairly significant ways (i.e., spatial explicit mapping vs. point-based estimates and different non-agricultural land cover classes) we believe it is useful to provide some general comparisons of overall estimates. We also conducted a validation of the SAF agricultural cover/use types directly to the NRI points. In general, we found similar estimates of the areal extent of land cover/use classes for 2012 to those estimated by the NRI (Table 11). In comparison to NRI, SAF slightly underestimates crop and pastureland. The SAF developed classes (urban and low-density) are estimated to be more (141M ac), as low-density residential use extends beyond those areas identified in NRI as urban (113M ac).

We also compared the trends of conversion from 1992 to 2012 of agricultural lands (defined in NRI as crop, pasture, and range to urban; and in SAF as crop, pasture, range, woodland to urban or low-density residential). SAF estimates 18.0M ac of conversion of urban to agricultural lands, compared to the NRI estimates of 24.5M ac. SAF includes additionally conversion to low-density residential, which shows that an additional 12.6M ac of agricultural land was converted.

To compare the patterns, not simply the extent, of 2012 land cover/use classification to the NRI, we validated the SAF against the NRI sample point locations to quantify the spatial classification agreement between SAF and NRI. Table 12 provides a cross-tab that shows the percent classification agreement between SAF and NRI point locations for the cropland, pastureland, rangeland, forestland and urban classes (the other classes are not directly comparable). Overall, the land cover/use datasets agreed about 83% of time for both the 1992 and 2012 time periods.

By cover/use class, the validation indicates that 74% of the SAF cropland type was also identified as cropland type by the NRI, with most of the confusion with other agricultural land cover/use types (pasture 8% and, rangeland 6%). Some of the land we identified as cropland may also have been enrolled in the Conservation Reserve Program for which SAF did not have spatial data. The comparison of SAF pastureland with NRI, as anticipated, was low (37%), because of the lack of distinct spectral signature of pastureland. We identified some of the pastureland from the NRI as cropland (16%), forest and woodland (15%), rangeland (13%) and “other rural” (8%). Seventy-two percent of the land we characterized as urban was also identified as urban by the NRI points. The comparison of “other rural” to NRI was 39%. The NRI “other rural” class includes other rural land (farmsteads and other farm structures, field windbreaks, barren land and marshland) and water areas (permanent water) in this category and is difficult to map spatially in SAF because it is a mixture of various cover and use types.

We also compared block-level housing density to NRI cover/use types (Table 13) as well as to NLCD use/cover types (Table 14). To examine regional variability in how SAF results compared to the NRI, we compared the estimates of urban and low-density residential for each state against the NRI urban (with 95% confidence intervals; Figure 13a and 13b).

Table 11. A comparison of the estimated area of land cover/use classes between our results (SAF) and the NRI for 2012 in millions of acres.

Land cover/use	SAF area	NRI area	% SAF of NRI
Cropland*	313.8	362.4	87%
Pastureland	108.4	120.7	90%
Rangeland	409.2	404.6	101%
Forest	328.5	411.0	80%
Woodland	80.1	-	**99%
Urban	71.5	113.3	63%
Water	43.4	52.0	84%
Federal	217.9	-	-
Federal (grazed)	158.4	-	-
Other	87.9	44.90	196%
Low-density res.	69.5	-	-
Agriculture classes	911.7	887.7	97%
Federal lands (all)	376.3	405.3	92%

Note: *SAF does not include Cropland Reserve Program acres in the cropland class (it goes into the other). **We included forest and woodland from SAF in comparison to NRI forest.

Table 12. A cross-tab (aka "confusion" matrix) of the SAF and NRI land cover/use classes at the NRI sample point locations for 2012. Note that we weighted the percentages to account for the unequal probability sampling design of the NRI. CRP = Conservation Reserve Program.

	NRI cover/use types in 2012								
SAF land cover/use types in 2012	Crop-land	Pasture-land	Rang-land	Forest	Urban	Water	Federal	Other Rural	CRP
Cropland	**74%**	16%	2%	1%	2%	0%	0%	9%	25%
Pastureland	8%	**37%**	3%	2%	2%	0%	0%	6%	19%
Range	6%	13%	**79%**	3%	2%	0%	3%	13%	36%
Forest & Woodland	3%	15%	5%	**77%**	4%	2%	2%	16%	8%
Urban	1%	2%	1%	1%	**72%**	1%	0%	6%	1%
Water	0%	1%	1%	0%	1%	**92%**	0%	6%	0%
Federal & Fed. Grazed	0%	0%	2%	1%	0%	1%	**93%**	2%	0%
Other rural	4%	8%	8%	7%	5%	4%	2%	**39%**	10%
Low-density res	3%	8%	1%	7%	13%	0%	0%	3%	1%

Table 13. Listing of the mean of block-level housing density for the NRI 2012 class types, nationally.

Value	NRI class	Housing density (units / km^2)
1	Cropland (cultivated)	3.2
2	Cropland (uncultivated)	7.6
3	Pastureland	8.3
4	Rangeland	1.4
5	Forest	8.5
6	Other Rural	11.5
7	Urban	410.8
8	Other Rural	15.8
9	Water	14.9
10	Water	6.4
11	Federal	2.9
12	CRP	1.0

Table 14. Listing of the mean of block-level housing density for the National Land Cover Dataset 2011 v3 class types, nationally. Note that the locations where these data were extracted were located at the ~800,000 NRI points. Also, because blocks can vary in size from 1-1000 acres, or because of mis-classification in the NLCD, some housing density can be reported for cover types where, at the individual pixel level, one would not expect a house to occur (e.g., water).

Value	NLCD class	Housing density (units / km^2)	Acres per unit
11	Water	3.7	66.7
21	Developed, open-space	159.1	1.5
22	Developed, low-intensity	469.2	0.52
23	Developed, medium-intensity	700.6	0.35
24	Developed, high intensity	515.5	0.47
31	Barren	7.6	32.51
41	Forest - coniferous	12.3	20.0
42	Forest - deciduous	7.2	34.3
43	Forest - mixed	10.0	24.7
52	Shrubland	2.6	95.0
71	Grassland	2.0	123.5
81	Pastureland	8.3	29.7
82	Cropland	3.2	77.2
90	Wetland - woody	9.7	25.4
95	Wetland - herbaceous	5.3	46.6

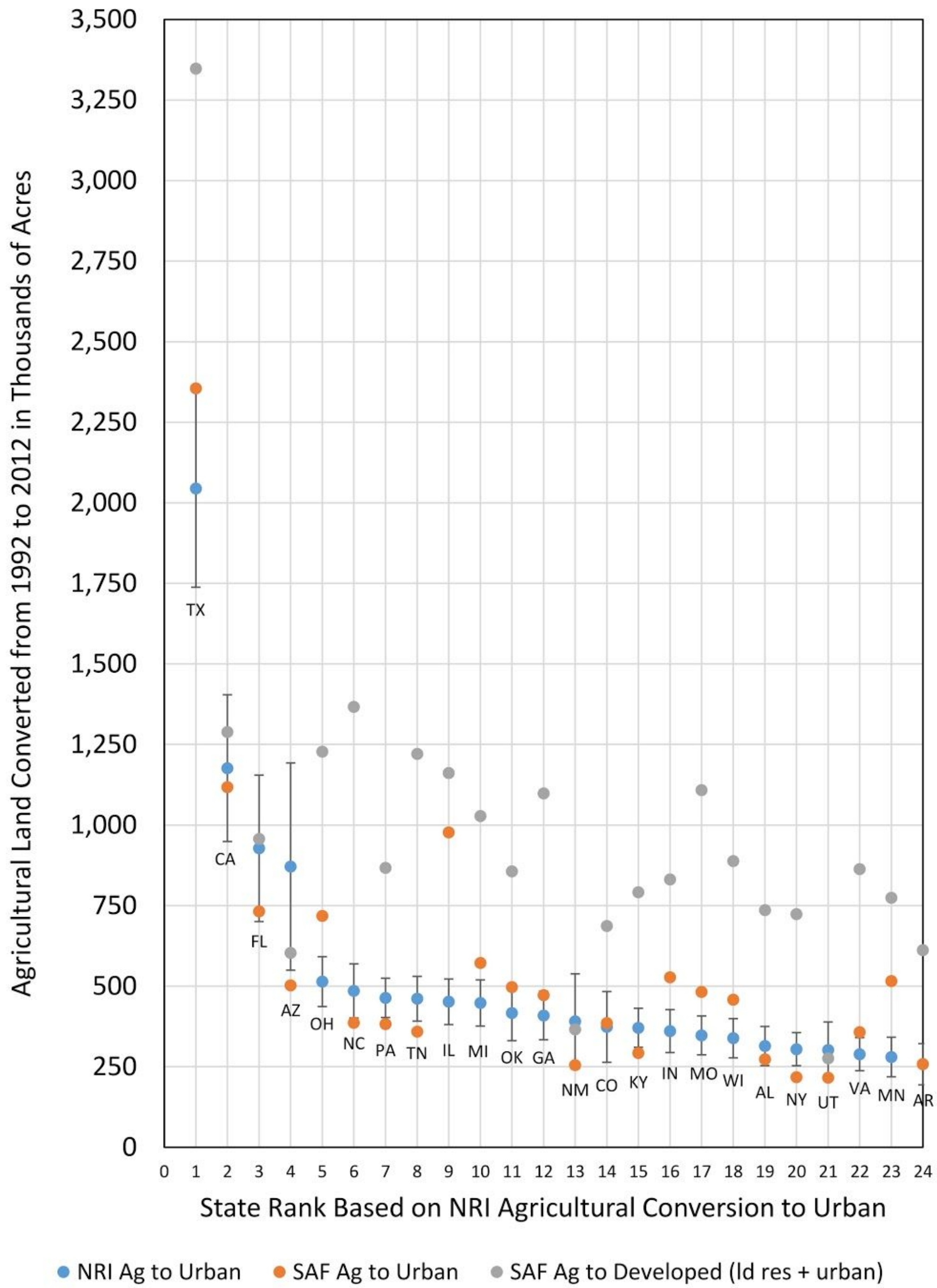

Figure 13a. SAF and NRI estimates of agricultural land cover/use conversion for the 24 states with the highest rates of conversion. The mean estimate of conversion from the NRI are shown as blue points, with error bars denoting the confidence intervals of the NRI estimates. The estimate of conversion of agricultural to urban land cover/use in SAF is shown as orange points, while the conversion to low-density residential ("ld res") and urban is shown as grey points. States where the estimates of conversion from SAF fall within the NRI error bars are called "high confidence" conversion estimates. Note that the y-axis scale is different than in Figure 13b.

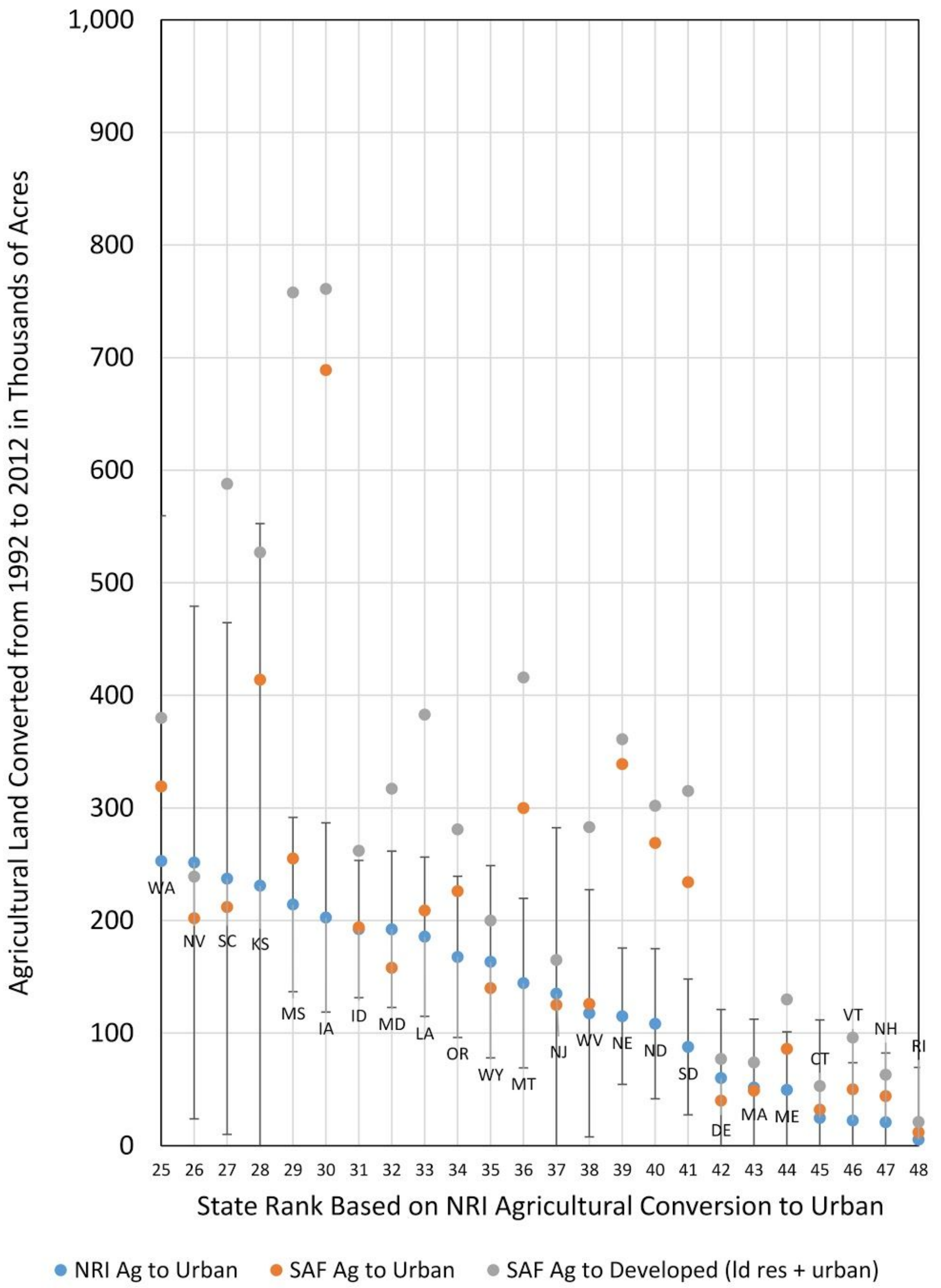

Figure 13b. SAF and NRI estimates of agricultural land cover/use conversion for the 24 states with the lowest rates of conversion. The mean estimate of conversion from the NRI are shown as blue points, with error bars denoting the confidence intervals of the NRI estimates. The estimate of conversion of agricultural to urban land cover/use in SAF is shown as orange points, while the conversion to low-density residential ("ld res") and urban is shown as grey points. States where the estimates of conversion from SAF fall within the NRI error bars are called "high confidence" conversion estimates. Note that the y-axis scale is different than in Figure 13a.

Discussion

We believe that the SAF datasets and related products provide valuable insight into the patterns, trends, conversion, and importance of agricultural lands. Our results are consistent with, and add value to, the national inventories of agricultural lands (especially the NRI) in multiple ways. Specifically, our results: (a) include three new classes important for representing patterns of agricultural lands, including estimates of woodlands associated with farm enterprise, public land grazing, and low-density residential; (b) include maps of grazing allotments on federal lands; (c) include a spatially explicit assessment of the extent of low-density residential development on agricultural lands; (d) show the spatial patterns of agricultural land uses and conversion to development in a consistent way over time; and (e) identify agricultural lands based on their productivity, versatility and resiliency to support intensive food and crop production (i.e., their PVR values). Moreover, we explicitly include uncertainty in the NLCD database into our suitability models that were used to build the SAF land cover/use maps.

Note that we primarily explored the net changes of agricultural lands. A small amount (compared to national totals) of lands were converted to cropland/pasture since 1992. We speculate that these recent cultivated lands, while locally/regionally important, likely occur on less productive (low PVR valued) lands. We recommend that this aspect be further explored in subsequent analyses.

Some of the key outcomes of our SAF effort include the following:

- America's farmers and ranchers make use of a diverse agricultural landscape which covers 55% of the land area in the continental US when we take into account both the non-federal and federal grazing lands. The broad extent of agricultural lands and their context is easier to both see and appreciate when mapped (Figures 7 & 8).
- Development converted approximately 31M ac of agricultural land between 1992 and 2012 -- about 1.7 times higher than previously documented by other national datasets. The major reason that the SAF estimates are higher than other datasets is that we account for losses of agricultural lands due to low-density residential use. Agricultural lands are converted incrementally, and those small changes make it difficult to understand the overall, somewhat inexorable and irreversible losses of agricultural land that are taking place. The best agricultural lands -- those with the right soil characteristics and growing conditions to support intensive food and crop production with the fewest environmental limitations -- comprise less than 17% of the total land area in the continental US. In less than one generation, the US lost nearly 11M ac of the best land for food and crop production. This is equivalent to losing 95% of California's Central Valley or 47% of the state of Indiana.
- Lands with higher PVR values were more at risk of being developed. Figure 10 shows the cumulative distribution curve of the PVR values of agricultural land in 1992 (335M ac) that remained in agriculture in 2012 contrasted with similar cumulative distribution curves of the PVR values of lands converted by low-density residential (13M ac) and urban development (18M ac). These distribution curves show that urban development and, to a lesser extent, low-density residential development occurred on land with

higher PVR values. The median PVR value of agricultural lands lost to development (0.39) was 1.3 times higher than the median PVR value of lands that stayed in production (0.31). The contrasting distribution curves also show the nation's best lands for intensive food and crop production (land with PVR values of 0.431 or higher) are disproportionately converted by urban and low density residential development up to a PVR value of about 0.51. It is interesting to note that above a PVR value of 0.51, the distribution curves converge, indicating that conversion is now proportional to the amount of agricultural land with these higher PVR values (less than 25% of agricultural lands in 1992). Although the losses are no longer disproportional, these lands with the highest PVR values continue to be converted. All of these cumulative losses could have serious implications for agricultural productivity and domestic food security in future decades.

Intended data uses and limitations

From the outset of the SAF project, we recognized that NRI provides critical information about the extent and trends of agricultural lands nationally. SAF is grounded on the platform of the NRI by driving the spatial patterns using county-level estimates of agricultural land cover/uses. SAF extends the NRI by spatially-explicit mapping those patterns, using detailed land use/cover maps (NLCD). We note that there is known uncertainty in the NRI cover/use estimates (e.g., included in Figure 13) and this is important to remember when comparing our results to NRI, especially with regards to the evaluation of conversion of agricultural lands to developed land uses. NRI has an urban cover/use, but not a low-density residential class, *per se*.

We believe the results of the SAF are the best available for spatial mapping of agricultural land cover/use nationally, and the quantification of uncertainty demonstrates that our results are well within established ranges of standards of accuracy (~85% from Anderson et al. 1976). However, as with any spatial analysis and mapping of this complexity, detail, and extent, improvements in the datasets remain. To this end, we identify two main sources of uncertainty.

First, the NLCD dataset is fundamental to the SAF product, and because we wanted to examine change over a longer time span (roughly a generation) we needed to use the NLCD for 1992, which is based on Landsat imagery, but was processed using different methodology as the NLCD v3 (2001-2011) series. Not surprisingly, this introduced some challenges in investigating change and conversion of agricultural land (which is a primary reason we carefully apply these data at sub-county scales). This is particularly true for handling roads, which are typically mapped as urban use/cover classes, even in rural areas. NLCD for 1992 did not include the rural roads (which are almost always not 30-m wide, and typically ~10-m wide) while NLCD for 2001 and 2011 did include rural roads. If we naively quantified change between these two products, we see a very large conversion of roughly 2-3% of the conterminous US; many to most of the roads present in 2011 also were present in 1992, though we do not have the data to quantify those changes across the US in a consistent way. Because cropland and pastureland typically extends up to and adjacent to rural roads, their estimated extent in SAF is slightly lower or more conservative than expected (and compared to NRI).

Second, low-density residential land that encroaches on agricultural production is challenging to map, especially from satellite imagery used by the NLCD. Residential areas occur across a gradient of densities (Theobald 2004), typically declining in density away from the urban fringe. Developed, urban classes from NLCD are typically mapped for densities of greater than 1 house per 1-2 acres, but suburban and exurban areas at lower densities are typically mapped as forest, shrubland, or grassland, rather than as a developed class. This effect of under-representation is especially pronounced in regions of the country with heavy tree canopy, such as the northeastern and southern US. Our mapping of low-density residential is an explicit attempt to map the areas that are not high enough density to be mapped as urban areas (with the notable exception of community agriculture and backyard gardens), but not low enough to be considered part of agricultural land use. Our mapping of low-density residential targets these "in-between" land uses which typically exclude agricultural production, although some "subsidized agriculture" likely remains. In support of this, we found that roughly 30% of NRI points classified as urban cover/use are outside of the NLCD developed (urban) classes. Also, we found that housing density mapped at the census block-level spreads across adjacent non-urban land use/cover types.

We produced the SAF products at a resolution of 30 m (or ~¼ acre), but we consider the minimum mapping unit to be about 1,000 acres, and we caution use of the data below this scale. Most importantly, to characterize broader-scale patterns and trends, we advise a minimum analytical (decision) unit to be at the sub-county level -- approximately HUC12 level (i.e., >1,000 acres). We recognize that there is some utility at using the data at relatively fine-scales, but caution that the interpretation of our results be used appropriately, particularly when applying the data to site-scale planning exercises. Calculating landscape change is particularly challenging, and we suggest using our data to quantify robust measures of change at county, state, and national scales. Fine-scale analysis should proceed under advisement of the data developers (CSP) on a case-by-case basis.

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