

Original Research

A Rapid Method of Examining Land Use/Land Cover at Small Industrial Facilities Using Four U.S. Department of Energy Sites as Case Studies

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Abstract

This work addresses the application of a method to examine the spatial extent of ecological resources and green space on small Department of Energy (DOE) sites and comparison to ecological resources and green space in the surrounding region. Increasingly, governmental regulators, resource trustees, and the public are concerned that federal facilities are protecting human health and the environment, including ecological resources on their sites. This paper uses the National Land Cover/Land Use Database to examine and compare land use/land cover on four small DOE sites in which environmental remediation is on-going. The



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main objectives were to: (1) examine the amount and type of ecological land use/land cover present on each site, (2) compare on-site land use/land cover with the surrounding region, and (3) compare land use/land cover among the four DOE sites that are undergoing remediation. The four sites selected are Knolls Atomic Laboratory (New York), Lawrence Livermore National Laboratory (California), Paducah Gaseous Diffusion Plant (Kentucky), and Portsmouth Diffusion Plant (Ohio). This paper provides a method that is useful for land managers and the public to evaluate land use/land cover on small energy sites or other energy facilities, as well as other contaminated industrial sites. All four DOE sites had a higher percentage of land that was developed (built or paved) than the surrounding 10-km and 30-km buffers, and the smaller sites had a higher percentage of developed land than the larger sites. On all sites the industrial developed land was consolidated, and wild land surrounded this developed land. Lawrence Livermore Laboratory had the lowest percentage (only 10%) of any wild ecological land other than developed and agriculture. Both Paducah and Portsmouth had nearly 60% of the sites designated as developed or agriculture. Although Paducah and Portsmouth had about the same percentage of forest (the climax community), Paducah had a significantly higher percentage of forest than the surrounding, largely urban, regions. This paper provides a method of examining wild lands on sites (and off-site) allowing decision makers, regulators, and the public to make more informed decisions about remediation, restoration, and land management. The method reduces overall time and personnel needed to do an initial evaluation of land use/land cover and potential ecological resources of interest.

Keywords

Ecological resources; land use/land cover; bioindicators; national land cover database; department of energy sites

1. Introduction

Developed nations, as well as other countries, have legacy wastes remaining from municipal, industrial, and nuclear facilities that have resulted in contaminated land requiring restriction or remediation. U.S. Federal and Tribal governments, as well as non-governmental groups and the public, are interested in converting contaminated land to productive uses [1, 2]. Recently, considerable attention has focused on legacy wastes from World War II, the Cold War and subsequent industrial development. The U.S. Government obtained land for the Manhattan Project to invent and build bombs [3], and additional sites were obtained to accommodate the nuclear arms race of the Cold War. National emphasis on secrecy resulted in large, undeveloped but protected buffer areas, and speedy production often resulted in poor waste management, resulting in extensive radiologic and chemical contamination of land and water—the “legacy waste”. The past practices spawned a need for massive “cleanup”.

Increasingly government agencies, resource trustees, and the public are interested in enhancing and protecting both ecological resources and green spaces on these lands, within and near communities [4]. Research by social and health scientists shows that “green spaces” near and within communities provide health benefits in addition to recreation and aesthetics [5, 6], including direct

benefits to mental health and cardiovascular health that lead to lower mortality [7-9]. Thus, maintaining and enhancing human health is an added benefit of preserving and enhancing ecological health of “green space” and natural ecosystems. Management goals include eliminating contaminated buildings and other facilities, removing or remediating contaminated soil, and cleaning groundwater to provide clean water and air. However, an important societal goal is to protect existing wild lands and ecosystems, and make formerly contaminated lands available for other uses [10-13].

Protecting ecological resources is especially important, particularly on the large U.S. Department of Energy sites (DOE) that have a high percentage of their land in natural, undisturbed lands that are largely uncontaminated [14, 15]. The large DOE sites, such as the Hanford Site, Los Alamos National Laboratory, Idaho National Laboratory, and Savannah River Site, as well as many other sites, have significant and rare ecological resources [16-19]. However, it also may be important to protect ecological resources and enhance green spaces in the smaller DOE sites or other energy facilities that are near or within suburban and urban communities. Such local regions may have fewer opportunities to reclaim green spaces. Having methods to evaluate both the presence of green spaces and the value of ecological resources is important not only for DOE, but for resource trustees and the public in surrounding communities [20-23].

This paper examines the presence and amount (percentages) of ecological lands and green spaces on four of the smaller DOE sites. Our objectives were to (1) assess the land use/land cover types on each site, (2) compare land use/land cover on sites with the surrounding 10- and 30-km bands, (3) compare land use/land cover among the sites, and (4) discuss the applicability of the method for other industrialized sites. The four sites examined are: Knolls Atomic Laboratory (New York), Lawrence Livermore National Laboratory (California), Paducah Gaseous Diffusion Plant (Kentucky), and Portsmouth Diffusion Plant (Ohio) [24, 25].

We used the National Land Cover Database [26, 27] because it maps land use/land cover for all of the continental U.S. The NLCD is conducted every few years and is freely available on line to anyone. The latter is important because it allows landowners (in this case DOE), regulators, natural resource trustees, public, and others to pose their own questions, using whatever scale is appropriate. It also provides examples of a methodology to examine land use on a site, including the presence of green space (wild or natural areas) compared to development on a site suitable for non-governmental industrial sites near or within larger cities. The method has proven useful in comparing ecological resources on the larger DOE sites [28-30]. The method, however, can also be used by other small nuclear or other energy facilities, as well as any small sites that are being considered for restoration, remediation, recreation, or development.

Ecological evaluations and assessments usually involve conducting detailed literature searches and field studies of the status and trends of specific species of interest, as well as examining rare and unique species assemblages and rare and unique ecosystems [31-33]. In many cases, such evaluations do not have the funds, personnel, or time for a full-scale ecological evaluation, especially for smaller sites, the ecologic values of which may be overlooked. The method presented in this paper allows for a relatively rapid comparison of habitats within a site, of habitats on and off-site, and for comparisons among sites. It provides a method that can be applied by a range of people in different disciplines and with different questions to address site-specific questions dealing with land use/land cover and the protection of wild spaces on industrial sites. It can be an important tool to communicate information to governmental and non-governmental agencies and the public about

ecological protection and green spaces provided on partially contaminated nuclear and industrial facilities and allow these same groups transparency of an evaluation tool. It also provides citizens or citizen groups with a tool to ask questions of interest about the land use/land cover and wild natural areas in their communities.

2. Background on the U.S. Department of Energy

Many of the larger DOE sites were built in remote areas close to rivers that provided cooling for nuclear reactors. Small portions (about 10%) of the large sites were industrialized for production of nuclear weapons and research, and the rest largely remained undeveloped but was patrolled for security purposes. These “buffer areas” were protected from intruders [34-36]. At the same time, smaller parcels of land were acquired for research and radionuclide production, often near towns or cities that also had a source of water [36].

From the mid-1940s to the late 1980s, producing warheads was the primary purpose of the DOE complex across the country, and environmental protection was not of primary importance [25]. About 1989, at the end of the Cold War, the U.S. DOE formed the Environmental Management Program (DOE-EM) to manage the DOE’s cleanup of the toxic and radiologic wastes [25, 36]. At that time, DOE-EM made Tri-Party agreements with EPA and state representatives that established cleanup milestones at many of the larger sites before site contamination was characterized. In the early period after the Cold War (*ca* 1989), governmental agencies and contractors were unaware of the enormous cleanup task. Since then, the DOE has cleaned up 91 sites at a cost of about \$170 billion (Government Accounting Office 2019) and continues to do so although there remain remediation tasks at 16 sites. Some of the larger sites may require 50 years or more to complete at a projected cost of over \$377 billion [23, 33, 37, 38].

Soon after its post-Cold War formation, DOE’s Environmental Management Division produced a report called “Charting the Course: The Future Use Report”. Its purpose was to develop stakeholder future use recommendations to serve in future decision making concerning environmental management [24]. The report states that future land use plays a role in clean up decisions and aids communities to reuse federal lands and emphasizes the importance of future land use to the Department’s commitment as a “steward of natural resources” ([24], p. 1). One important mission of the DOE is to protect human health and the environment [37]. The goal of protecting human health and the environment thus includes removal of contamination, protection of existing resources and reclamation (remediation, restoration) of existing contaminated lands [39-41]. In some cases, degraded land can be reclaimed by allowing the damaged land to undergo natural succession to the natural climax community and monitored natural attenuation of contamination [42]. The climax community refers to the natural vegetation that will exist at a place given the local geological and climatological conditions, such as deciduous or coniferous forest, shrub-steppe, grassland, or desert [43].

The method described in this paper was initially developed to evaluate ecological resources on the U.S. DOE’s Oak Ridge Reservation [28, 29].

3. Study Sites, Materials and Methods

3.1 Study Sites

The four DOE sites described are small in comparison to INL, Hanford, and Savannah River (measured in hundreds of square miles), but represent a size range from about 50 to almost 4000 hectares. These sites are located in different parts of the U.S. (Figure 1) and would have had different vegetation in when DOE took possession. The former two had a nuclear weapons mission but were also engaged in research and development, while that latter two had an important uranium enrichment mission. While cleanup is continuing at all four sites, the former two have a key future federal mission of research and development, while the latter two are being cleaned up and developed for multiple purposes, including commercial uranium enrichment at Paducah, as well as having a potential interim storage mission [24, 25].

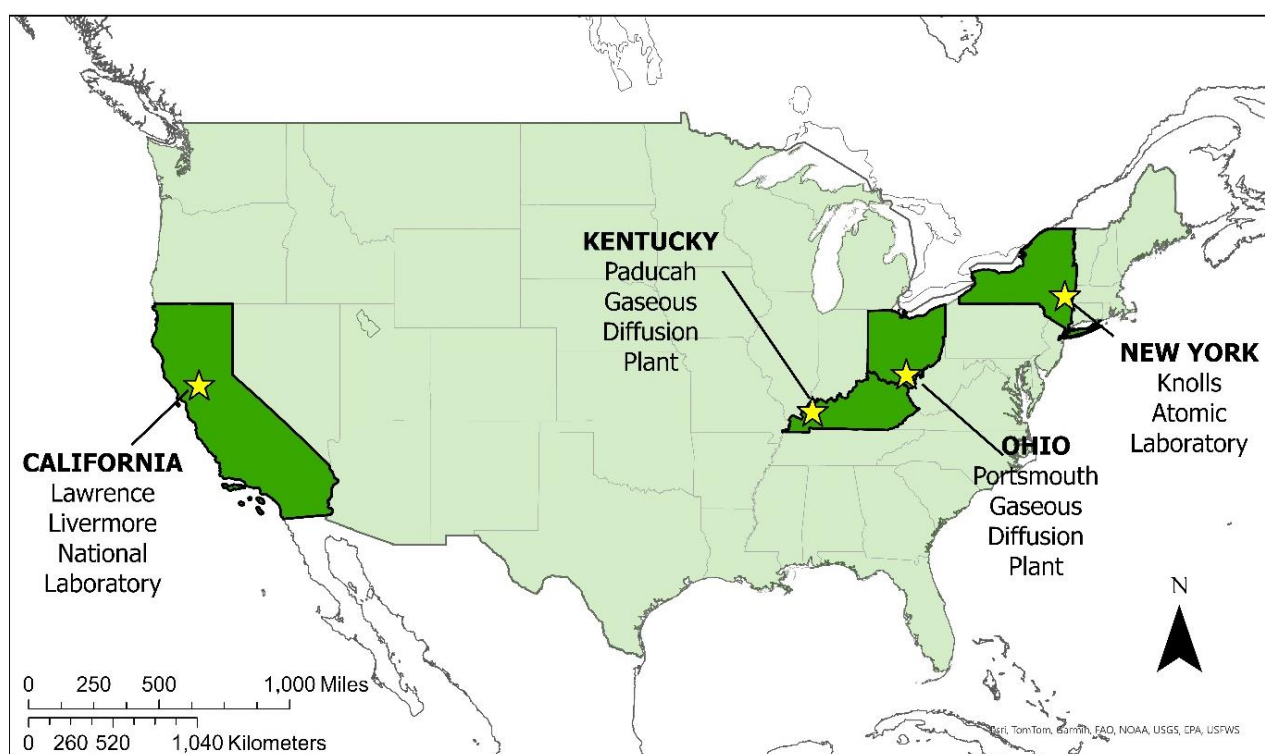


Figure 1 U.S. map showing the location of the four Department of Energy (DOE) sites discussed in this paper.

3.1.1 Knolls Atomic Laboratory

Located in Niskayuna, New York State, about 3.2-km from the city of Schenectady, the Knolls Laboratory occupies 53 ha on the banks of Mohawk River that flows along the site, about 30-km above its confluence with the Hudson River. The area immediately surrounding the site is a mixture of light industry, farms, parks, and suburban residential. The laboratory began operations in 1946 and now houses chemistry, physics, and metallurgical laboratories in addition to administrative offices, machine shops, cooling towers, and waste storage [44]. The main function is research and development and operation of naval nuclear propulsion engines [44]. There is no drinking water wells on site; potable water comes from municipal water systems. Water for cooling of the Knolls

Laboratory comes from the Mohawk River [37]. Current cleanup work includes facility deactivation and decommissioning [37, 45-47]. Knolls are expected to remain a federal research facility.

3.1.2 Lawrence Livermore National Laboratory (LANL)

Lawrence Livermore National Laboratory (329 ha) was established in 1952 as a multidisciplinary research center that focused on weapons development, security, and stewardship [47-49]. LANL has an ongoing mission as part of the National Nuclear Security Administration (NNSA) [48]. LANL is located within an urban and wine production region in California. It is within an area of steep hills and ridges separated by ravines and is home to several state endangered species [48]. Congress has mandated the demolition of several excess buildings, and remaining remediation also includes contaminated soil areas [50]. Current cleanup work involves soil and groundwater remediation [47].

3.1.3 Paducah Gaseous Diffusion Plant

Paducah Gaseous Diffusion Site (1387 ha) is located in rural McCracken County, Kentucky, just south of the Ohio River. Constructed in 1950 on a former munitions site, Paducah enriched uranium from 1952 to 2013 [51]. Paducah has completed building removals on site [50]. Current cleanup work involves special nuclear materials and spent nuclear fuel, and facility deactivation and decommissioning [37]. The site is in the process of conducting a joint study with the Paducah Area Chamber of Commerce, leading to its first land transfer for reindustrialization [52]. Conservation, recreation, and industrial use were the preferred future land uses in their land use/land cover plan [53]. Paducah is expected to conduct uranium enrichment for commercial users.

3.1.4 Portsmouth Gaseous Diffusion Plant

Portsmouth site (3762 ha) is in the Ohio Valley along the Sciota River, and was the third gaseous diffusion plant in the U.S. It began enriching uranium in 1956, producing highly enriched weapons-grade uranium. In the 1960s it produced fuel for commercial nuclear power plants [54]. Much of the land is scheduled for economic diversification, asset transition and business and other industrial development [54]. Current cleanup work involves special nuclear materials and spent nuclear fuel, and facility deactivation and decommissioning [37]. The future vision is for multiple industrial uses. Portsmouth has conducted extensive habitat mapping of its land [55]. Land transfers have also occurred at Portsmouth.

3.2 Protocol

3.2.1 Overall Protocol

A method that allows a relatively rapid evaluation of overall ecological resources on a site was required that could be used at sites across the country with different habitats. The method selected was to use the National Land Use/Land Cover Database [26, 27]. This has the advantage of defining different land use/land cover categories, including ecological vegetation types equivalent to local/regional climax vegetation [11]. After selecting study sites partly based on sites still requiring remediation, we (1) examine land use/land cover from the NLCD database on each study site, (2) examine the percentage of each land use/land cover categories within each site, (3) compare the

percentage of each land use/land cover categories on-site and off-site (regionally), and (4) compare land use/land cover among the four sites.

In previous work the method has been applied to large DOE sites in which only approximately 10% of the land was industrialized for nuclear weapons production and research [28, 30]. The four sites described in this paper were selected because remediation is ongoing, there is a range of areas (in ha), they have different climax vegetations, they have a range of missions, and they are in suburban and urban location that increase the relevance to other former industrial sites across the U.S. and elsewhere.

3.2.2 Selection of Land Use/Land Cover Indicators and Bands of Analysis

The land use/land cover categories in the National Land Use/Land Cover Database [26, 27] differ across the country, and the database provides different layers of consideration [11]. For example, the eastern U.S. sites have forest as the primary ecological land cover (climax vegetation), while mid-western interior sites may have grassland, and western sites may have desert or shrub-steppe [56]. The key feature of the methodology and present analysis is that the climax vegetation can be examined on-site and off-site, and among sites, even though it differs. An assumption is that the prevailing climax in the region ideally should exist both on-site and off-site.

In this analysis, a 10-km band and a 30-km band were drawn around each site, and the land use/land cover in each band was used for comparison with on-site land use/land cover. The 10-km band was selected because it includes neighborhoods, towns, or cities that are adjacent to the site and might suffer harm or benefit from contamination or activities on the site. The 30-km band was chosen to capture more of the regional ecology, especially in more rural areas where agriculture or protected lands might be included. These buffer distances are arbitrary, but they allowed comparison of land use/land cover types on different sized DOE sites. Other buffer band area sizes can be selected by managers or others for different locations and questions [28, 57]. The U.S. Geological Survey has distributed the multi-resolution NCLD at about every 5-year intervals since 1992 (www.mrlc.gov/data/nclد-land-cover-conus-all-years).

3.2.3 Analysis of the NLCD (2019)

The NCLD has several levels of analysis of land use/land cover. The levels are at different gradients of land use/land cover. In other words, the GIS maps have a number of different finer divisions (called levels) of the land use/land cover types. For example, at the largest scale the land cover might be defined as forest, and at a finer scale it is segmented into coniferous forest and deciduous forest. At a still finer scale it is segmented even further to denote small patches in the forest of different habitats (e.g., grassland). Different maps show the land use/land cover designated at a finer scale. Depending upon the question being asked, a level is determined.

For the DOE sites examined in this paper, there are different types of ecological lands and different levels of development (low to very dense; [26, 27]). For the four sites examined, there were usually about 15 land cover types identified (Level 1, NLCD 2019). For some analyses we used all land cover types listed and for others selected types were combined for specific questions. For example, initially, we examined forest (all types); development (all types); and other habitats and then examined forest and development types separately. The dataset distinguishes three types of forest: deciduous (at least 75% deciduous); coniferous (at least 75% coniferous); and mixed (not

having 75% of any forest type), as well as four types of development: (1) open space = parking lots, parks, ballfields, tennis courts, and other open areas; (2) low intensity = a mixture of constructed materials and vegetation, with 20-49% impervious surfaces and single family houses; (3) medium intensity = constructed materials and vegetation, with 50-79% impervious surfaces; and (4) high intensity = highly developed areas, mostly structures and with impervious surfaces of over 80% of the land (from [27]).

To determine differences among the three areas (site, 10-km band area, 30-km band area), we used Analysis of Variance (ANOVA). To perform the ANOVA, each area (Site, 10-km area, and 30-km area) was divided into equal area polygons, each of which was assigned a cover type (Table 1). Each polygon was assigned a land use/land cover type (e.g., type of forest), and each polygon contributed equally to the overall analysis. At the edges, if a polygon was not complete, it contributed a percentage to the overall total. To ground-truth the maps and analyses, we used Google Earth satellite data to examine areas that seemed to be unusual when compared with the surrounding habitat (i.e., a small block of open area surrounded by forest with no roads or obvious human connections).

Table 1 Sizes of the DOE sites examined and the polygon number for each area. Polygon sizes were determined by the patchiness of land use categories and were used for determination of relative land use/land cover. Some sites have small-sized land use patches, requiring the use of more polygons than sites with more homogeneous land use/land cover types. Knolls Atomic Laboratory had very small land use patches, requiring smaller polygons to describe the land use/land cover types, whereas Portsmouth had large land use/land cover patch types, requiring fewer polygons. For this study the comparisons were between the site, 10-km band and 30-km band, not among the four sites.

DOE Site	Area (ha)	Polygons on site	Polygons on 10-km band	Polygons on 30-km bands
Knolls Atomic Power	53	64	1,1530	108,024
Lawrence Livermore Laboratory	329	122	9,623	72,395
Paducah Gaseous Diffusion Plant	1,387	614	14,602	80,418
Portsmouth Gaseous Diffusion Plant	3,762	295	9,397	57,869

To check which groups differed significantly, a post-hoc Tukey's test was used to test the difference between each site and the 10-km buffer, and between the site and the 30-km buffer. The data were analyzed using Python (version Python 3.8 and Spyder Anaconda). We also used the Wilcoxon Two-Sample Test for differences among land use types [58]. Non-parametric tests were used to compare cover types on- and off-site because these are best suited for samples with non-normal distributions [58, 59]. We considered $p < 0.05$ as significant in terms of not meeting the hypothesis that the means could not be determined to be significantly different.

4. Results

The data are considered at two scales: the sites themselves and the surrounding regions. The surrounding regions examined were the 10-km and 30-km bands around each site. The other

distinction is that Knolls and Livermore are DOE National Laboratories with on-going research and development and nuclear missions, while the two smaller sites are likely to have commercial facilities and diverse energy portfolios.

4.1 Knolls Atomic Laboratory

Land Use on Knolls Laboratory is illustrated on Figure 2. The map of the site (top figure) shows that the industrial area is compact, with the agricultural fields to the southeast. The percentages of developed, agricultural, and wild lands are shown in Table 2. The site itself is adjacent to the Mohawk River, providing water for industrial operations. Most of the undeveloped on-site land is forest and agriculture, but the agriculture is mainly abandoned fields and overgrown fields with some small shrubs.

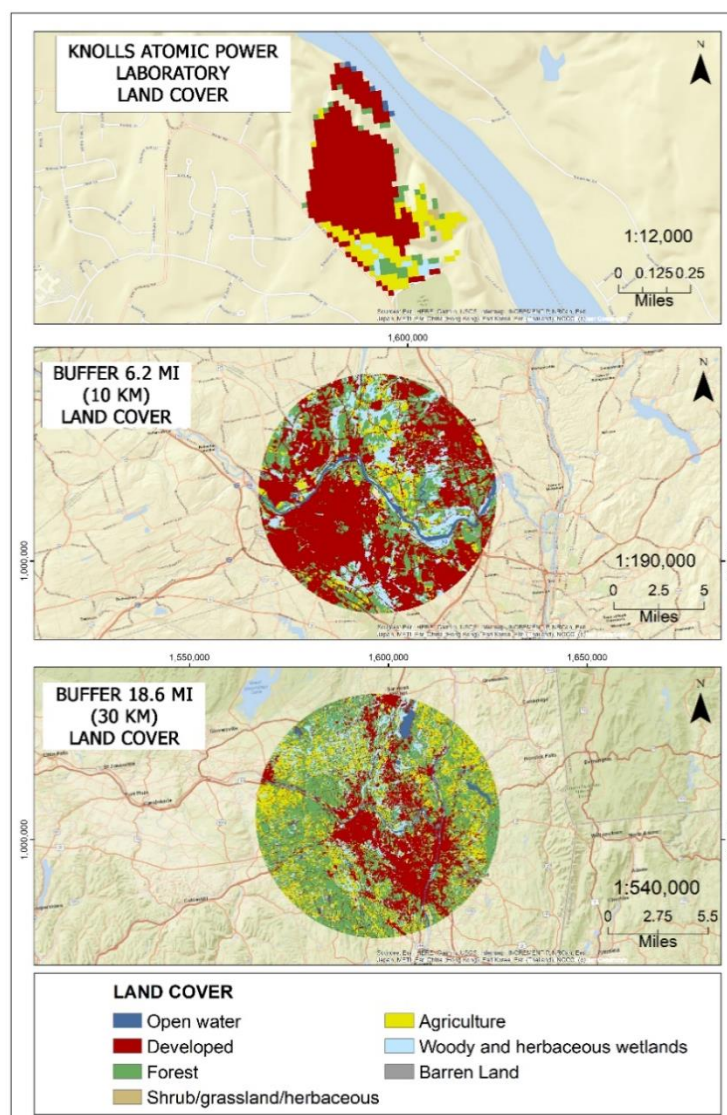


Figure 2 Land cover/land use types at Knolls Atomic Laboratory near Schenectady (New York), including a site map, 10-km buffer map, and 30-km band map. The Knolls Laboratory is in the town of Niskayuna. The Mohawk River winds from the north down adjacent to the Knolls Laboratory, down to where it joins the Hudson River on the south-eastern side of the map.

Table 2 Major land use/land cover types on four DOE sites and their 10-km and 30-km buffers. The X^2 comparing types on site with each buffer is shown in the buffer column. These are percentages of the total area (total = 100%).

Land cover/land cover type Percentage	DOE site	10-km buffer band	30-km buffer band
Knolls Atomic Laboratory			
Developed	68%	51%	25%
Agriculture	20	7	19
Forest	7	24	40
Shrub/scrub grassland	<1	<1	2
Wetlands	3	14	11
Other	2	4 (mainly open water)	3
X^2 (p)		21 (0.02)	21 (0.02)
Lawrence Livermore Laboratory			
Developed	90	19	17
Agriculture	0	2	14
Forest	0	4	16
Shrub/scrub/grassland	10	73	50
Wetlands	0	<1	<1
Other	0	2	3
X^2 (p)		22 (0.02)	21 (0.02)
Paducah Gaseous Diffusion Plant			
Developed	34	12	8
Agriculture	25	56	51
Forest	34	17	24
Shrub/scrub/grassland	<1	<1	<1
Wetland	5	8	11
Other	2	7 (mainly open water)	6 (mainly open water)
X^2 (p)		24 (0.04)	21 (0.02)

Portsmouth Gaseous Diffusion Plant			
Developed	50	8	7
Agriculture	8	29	22
Forest	33	58	66
Shrub/scrub/grassland	5	3	3
Wetland	<1	<1	<1
Other	4	2	2
X ² (p)		23 (0.0305)	21 (0.0172)

Note. Although wetlands account for less than 1% at some sites, it is important at Knolls and Paducah, so is included.

The middle map illustrates the relatively small size of the Knolls Laboratory in relations to the buffers; the 10 km band (the small dot in the center is the Knolls Laboratory) shows the urban areas Schenectady, Albany and Trop that surround the site, and the great amount of water (the Mohawk and Hudson Rivers with backwaters and wetlands) (Figure 2). Although the Knolls Laboratory is located in an urban and suburban area, the 30-km band indicates substantial agricultural and forested land (Figure 2).

While the map provides a visualization of the habitats and is useful in providing an overall picture of the placement and amounts of different habitats, it does not provide quantitative information useful for planning. Figure 3 shows the percentages of each land use/land cover type for the Knolls Laboratory, and for a 10-km band and a 30-km band around the site. The quantitative data are given in Table 2. The table also provides the major land use/land cover types of the other three sites to allow a quick comparison. The land use/land cover on Knolls is significantly different from the surrounding 10-km and 30-km buffer. The Knolls Laboratory has more developed land and has significantly less forest and wetlands than both buffer bands. Although 20% of the site is listed as agriculture, it is mainly abandoned fields or fields that are overgrown with small shrubs that provide more green space and ecological value than the numbers suggest (JB pers. observation).

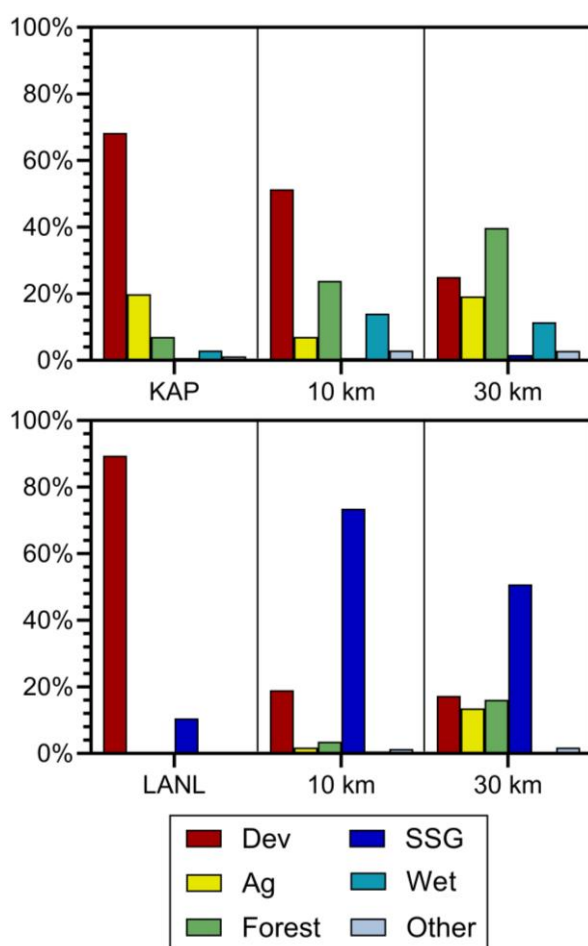


Figure 3 Land use/land cover for the Knolls (KAP) and Lawrence Livermore National Laboratories (LANL). Both sites are more highly developed than the buffers. The Knolls has some agricultural land that is abandoned fields, while the 10-km band has less.

4.2 Lawrence Livermore National Laboratory

Lawrence Livermore National Laboratory has the highest percentage (90%) of developed industrial land of the four sites examined in this paper. Further, the site is relatively square (Figure 4). The remaining area on site is shrub/grassland in a narrow strip on the north and western edge. The Laboratory is bordered by some urban areas but is surrounded by shrubland and forest (10-km and 30-km bands around the site, Table 2 and Figure 3). Thus, unlike the Knolls Atomic Laboratory, there is virtually no wild habitat on site. Much of the habitat in the surrounding region is shrub/scrub and grassland in the 10-km (74%) and 30-km (51%) buffers (Table 2). There is no forest on the Lawrence Livermore National Laboratory, but 4% on the 10-km buffer and 16% on the 30-km buffer.

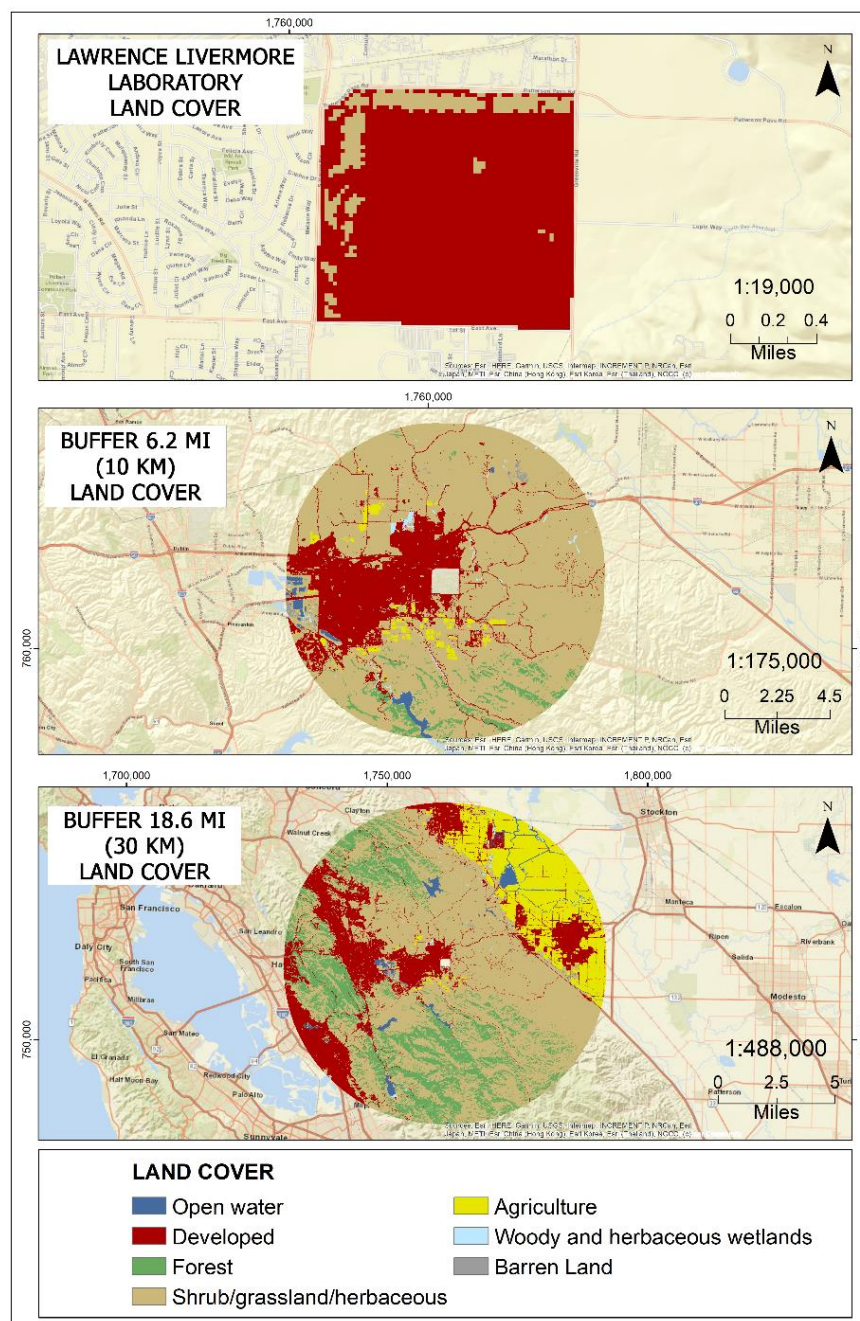


Figure 4 The industrial area of the Lawrence Livermore National Laboratory (top) takes up 90% of the land area. The laboratory is part of the larger Livermore area in California.

4.3 Paducah Gaseous Diffusion Plant

The industrial area of the Paducah Gaseous Diffusion Plant is one block, surrounded by mainly agriculture land and little remaining forest (top panel of Figure 5). Both the 10-km band and the 30-km band are largely agriculture and forest with relatively few towns (Figure 5, Table 2). Paducah does have a higher percentage of forest on its site (35%) than the two buffer bands around the site (less than 22% each, Table 1, Figure 6). Forest would be the natural climax vegetation. The two buffer areas have less development (industrial and residential); they have only 12 and 8% developed (Figure 5). Agriculture makes up 56% of the 10-km buffer, and 52% of the 30-km buffer (Table 2). Of the agriculture, most is cultivated crops (44% in 10-km and 38% in 30-km).

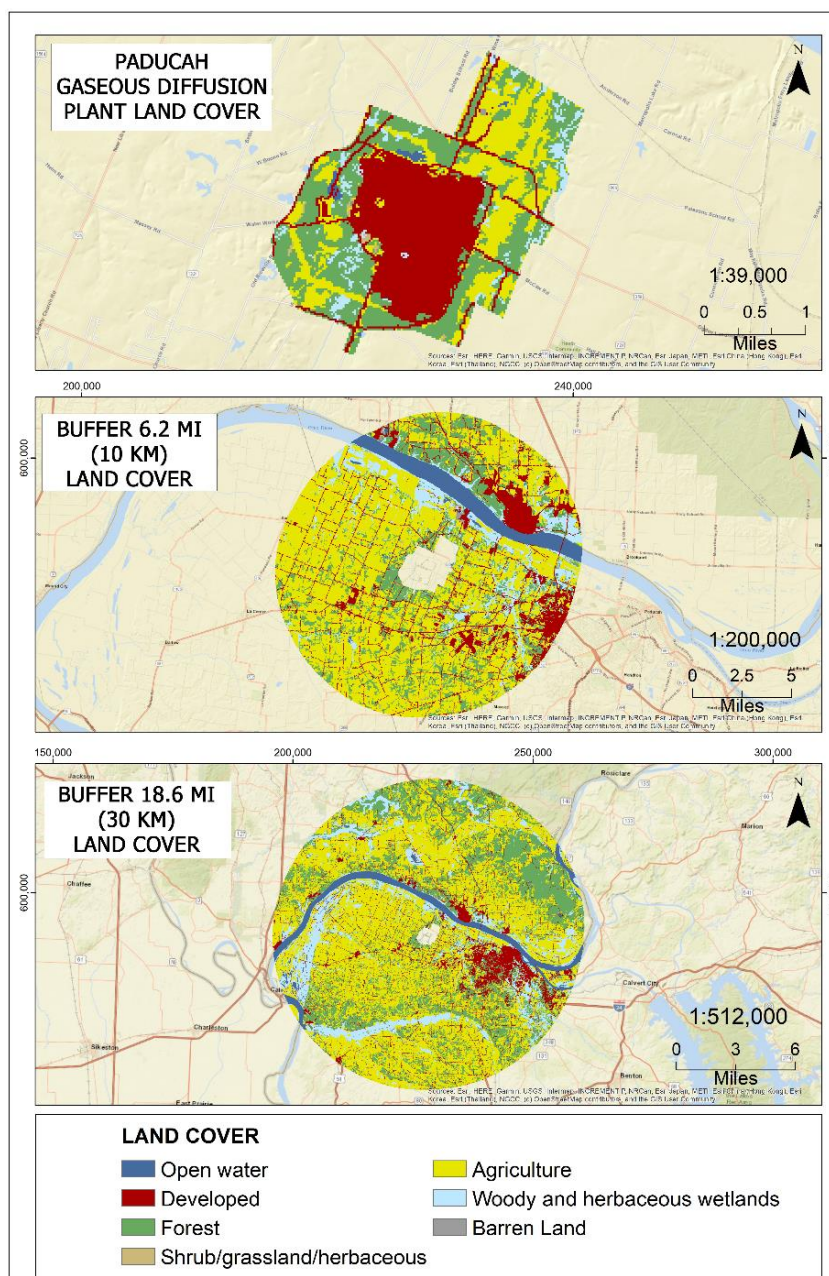


Figure 5 The industrial area of Paducah Gaseous is central on the site and is surrounded by agriculture and forest habitat. The Diffusion Plant is about 10-km from the center of the city of Paducah, Kentucky. It is only a few kilometers from the Ohio River.

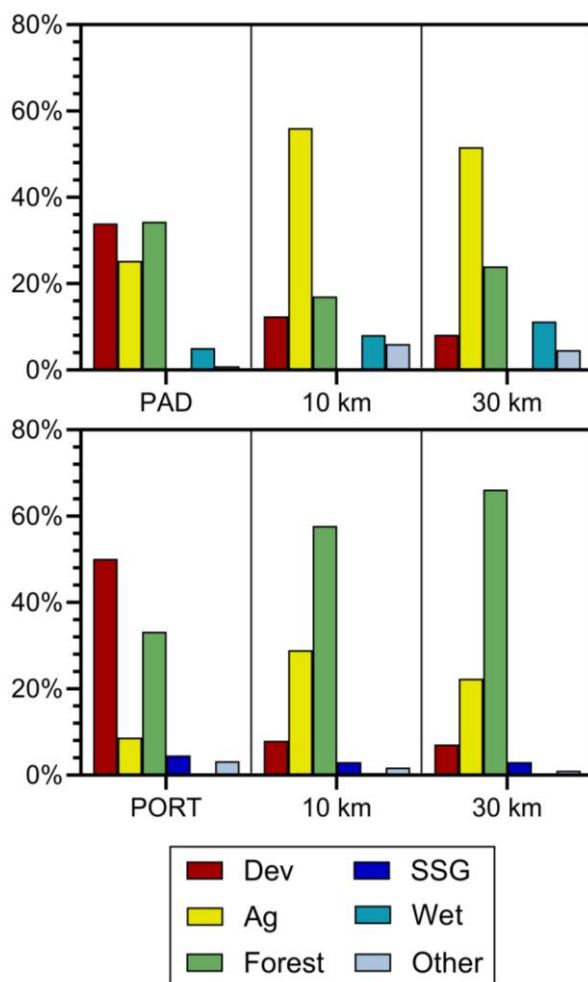


Figure 6 Comparison of land use/land cover on Paducah (PAD) and Portsmouth (PORT). Both sites have more development on their sites than the surrounding regions. Paducah had a higher percentage of its site in forest (and Portsmouth has less) than the surrounding regions.

4.4 Portsmouth Gaseous Diffusion Plant

The industrialized section of Portsmouth (50%) is in one block and is bordered on three sides with native vegetation including deciduous forest (33%) with small amounts of mixed forest, shrubs, and grassland (Figure 7, Table 2). There is also about 9% in pasture or hay fields, which may also be abandoned fields. In contrast to the Portsmouth Site, 58% of the 10-km buffer, and 66% of the 30-km buffer is deciduous forest (Table 2). Most of the rest is agriculture (29% in the 10-km and 22% in the 30-km buffers). Of the agriculture, 36% is cultivated crops in both buffer areas, and the rest is pasture or hay farms.

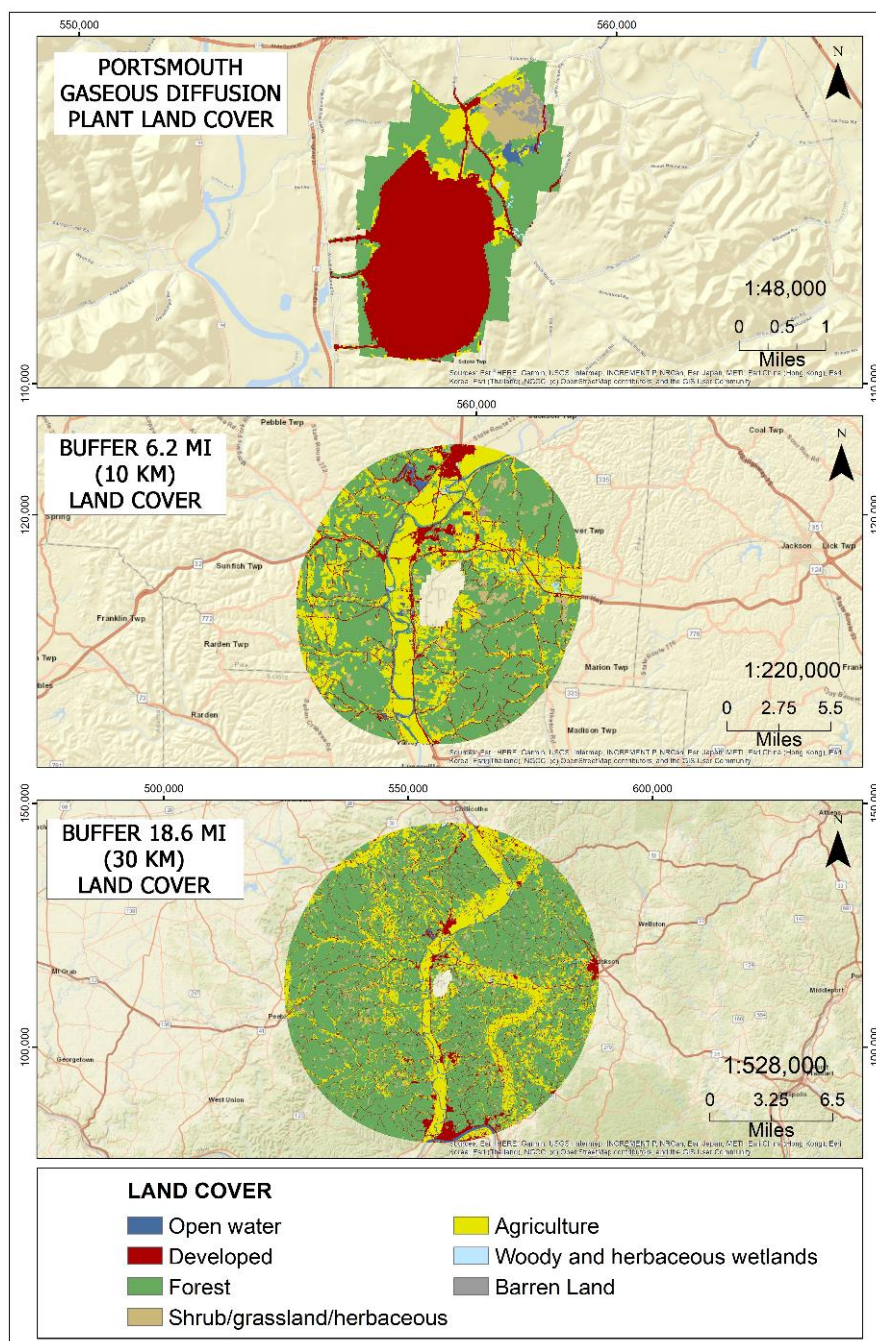


Figure 7 The industrial area of the Portsmouth Gaseous Diffusion Plant is also in a solid block, with forest surrounding most of the site. The Scioto River flows by the plant. The yellow fingers on the 10-km and 30-km bands are along the small rivers; agriculture primarily follows these rivers and streams and is often surrounded by forests.

4.5 Comparison of Land Uses Among Sites

The percentages of land devoted to different land uses and land cover are shown in Table 3. The two smaller sites (Knolls and LANL) have a higher percentage of developed land than the two larger sites. Paducah and Portsmouth both have over 30% of the sites in forest, but Paducah has about 24% in agriculture. Only Knolls and Paducah have much agricultural land, although the lands around

Knolls are largely abandoned fields. Further, none of the sites have a very high percentage of wetlands.

Table 3 Comparison of Department of Energy (DOE) sites examined, along with the percentage of different land cover types. The smaller-sized sites have higher percentages of development and lower percentages of wild areas and climax vegetation (forest). None of the sites have extensive wetlands. All numbers are areas in hectares (100 ha = 1 sq.km).

DOE Site	Total Area (Ha)	Developed	Agriculture	Forest	Shrub/scrub Grassland	Wetlands	Other
Knolls Atomic Power	53	68	19	7	1	3	2
Lawrence Livermore National Laboratory	329	89	0	0	11	0	0
Paducah Gaseous Diffusion	1,387	34	25	34	<1	5	2
Portsmouth Gaseous Diffusion	3,762	50	9	33	5	<1	3

5. Discussion

This paper examined land use/land cover at four DOE nuclear and research sites as case studies to demonstrate a method of overall land use/land cover analysis that may be useful for other industrialized sites. The sites varied in size, location, and past activities, as well as future missions. The data and analysis provide proof of concept for decision makers, land managers, and the public to improve overall decisions about remediation, restoration, and future use of the sites.

We make one important distinction that relates to overlap in land use/land cover categories. Land use refers to how people are using the land (e.g., development, agriculture), land cover refers to natural vegetation (e.g., forest, desert). However, some land cover types can be used for other purposes while still retaining the main land cover type. For example, one of the main land cover types on many DOE sites is forest, but people could also “use” part of this land for recreation without destroying it or changing it. Similarly, at another DOE site, Idaho National Laboratory, one of the major land cover habitats is shrub/scrub, but more than half of it is used for grazing cattle [24, 45]. The cattle may serve to replace the large numbers of large grazing animals that once roamed the west.

5.1 Individual Sites and Comparisons Among Sites

Future land options and cleanup levels are inter-related. There may be risk to people and biota from remaining contamination [24]. While this is not a focus for this paper, we note in passing that human health assessments have been completed for these sites [60, 61] as well as for biota [62, 63]. These data provide a clear indication of current land use/land cover and vegetative cover. There are clearly differences based on location and mission, as well as available space. The two smallest sites (Lawrence Livermore and Knolls Atomic Laboratory) have the highest percentage of developed,

industrialized land. They also have mainly abandoned fields, grassland and shrubs, rather than the climax vegetation of forest. Both have future research and development missions. Remediation on these sites is largely removal of old contaminated buildings and facilities. Lawrence Livermore and Knolls Atomic Laboratory have little opportunity for protection of ecological resources, different future land uses, or critical ecological resources or species. However, the Knolls facility must protect the Mohawk River because it is located on its banks.

In contrast, the two gaseous diffusion sites (Paducah and Portsmouth) have a lower percentage of developed land. The habitats on these two latter sites include agricultural land and forests, typical of the region generally. Because there is native habitat on these two sites, there is the potential for conservation and preservation of habitat. These habitats could also be used for recreational uses, as well as for land transfers to businesses and other industrialization.

5.2 Land Use/Land Cover Past and Present at the Four Sites

While the method is obviously not useful for a site or property that is entirely industrialized (e.g., all paved or impervious surfaces), it is applicable to smaller sites that have some green spaces that might be of interest to workers on the site, site neighbors, and other community members, as well as for a potential ecological value to surrounding ecosystems and community members. Like many industrial sites across the U.S and elsewhere in the world, these facilities are decades old and were developed when populations were sparser and green spaces were viewed for development potential. In the 1990s the DOE Future Land Use Report [24] laid out how sites thought the land should be used in the future well before the sites were characterized, and without the benefit of knowing how surrounding land would be developed or used in the future. Particularly problematic was the lack of information on contaminant sources and pathways of exposure. Even so, it is useful to compare the uses considered in the 1990s with present plans (Table 4). Each site described in that report had a map of the suggested future land uses. The initial report provided simplified maps showing the location of industrialized areas and open space areas, while the current NLCD maps provide detailed maps of land use, including levels of development and types of “open spaces” in terms of the dominant vegetation. The intent of this table is to show that even in the 1990s DOE and stakeholders envisioned a range of land uses.

Table 4 Future land use/land cover as described in the 1996 Future Use Report (DOE 1996).

Site	Land use/land cover as Describe in Future Use Report (DOE 1996)
Knolls Atomic Laboratory	Not included
Lawrence Livermore National Laboratory	One large NE block of industrial/commercial, with other areas of open space, ecology, open space buffer zones
Paducah Gaseous Diffusion Plant	Central industrial/commercial with surrounding recreational, storage/disposal, and open space
Portsmouth Gaseous Diffusion Plant	Large central section of industrial/commercial with surrounding areas of open space.

Over time, with increased agency and stakeholder discussions, the actual land use/land cover and expected future use has been refined, and in many cases, they have recent land use plans. In

some cases, land use preferences have shifted. For example, the Knolls industrial facilities have remained the same as the surrounding area was already developed and residential. However, Lawrence Livermore has increased in size as there is no longer a border around the industrial site that has open space and ecological resources.

Paducah and Portsmouth had similar missions and future land use plans. While Paducah has maintained open space, Portsmouth has not maintained an industrial central area, although it has open space on some sides. Both have maintained the same percentage of forest. Portsmouth, although, has a lower percentage of other wild habitats, has the same percentage of forest as Paducah, and forests occur in large patches. Large patches of forest are usually of high quality because there are many species that require forest, particularly neotropical migrants [64-66]. Fragmented forest often leads to an increase in invasive species [67]. These two sites illustrate the importance of not only looking at the percentage occurrence of a particular climax vegetation (e.g., forest) but also examining patch size and connectivity among patch sizes.

5.3 Comparison of Land Use/Land Cover with Surrounding Regions

A second objective was to compare current land use/land cover on the four sites with the current use in the surrounding regions (10-km and 30-km buffer bands). For all sites examined, there were significant differences between the use of land and land cover of the site compared to the two buffer areas (10-km and 30-km). In all cases, a higher percentage of the land was developed; all sites (except Lawrence Livermore) had agriculture on site, but in the case of Knolls Laboratory, the agricultural fields were mainly abandoned. The smaller sites (Knolls Laboratory, Lawrence Livermore) had a higher percentage of developed land than the larger sites (Paducah and Portsmouth).

One key observation in comparing the three sites with forest is that only Paducah has a higher percentage of forest on its site than the surrounding buffers (both 10-km and 30-km). Some of the forests were in large patches, with obvious advantages for some species that require interior forest. This suggests that DOE and community agencies, as well as the public, should consider whether these should be further protected.

5.4 Management: Ecological and Social

It is sometimes customary to examine the ecological, social, and economic advantages to developing a useful metric (or bioindicator). Economics is not the focus of this paper; however, we suggest that the method developed in this paper is a rapid assessment that could indicate whether a full-scale ecological evaluation would be necessary. This first step could well save money in terms of future decision making. Agency personnel, regulators, and the public can have a clear, common concept of how much land on the site is ecological, and whether it includes climax vegetation. Further, understanding of the both land cover and land use on the site will aid in making science-based decisions about management, remediation, restoration, and preservation/recreation. Inclusion of ecological data early in the decision-making process could save costly restoration costs later.

5.4.1 Ecological

Having a quick method to determine the amounts and percentages of major wild or green spaces on an energy facility or industrial site is a first step in any evaluation of the risk or potential harm to ecological resources. Using the NLCD provides an overview of the percentage of different types of land use/land cover. Land cover is very useful because it distinguishes diverse types of wild areas, such as grassland, shrub-scrub, and forest, among others. Knowing the percentage of each ecological ecotype (e.g., forest, grassland) will allow ecologists to quickly determine whether the habitat contains the local climax vegetation. For example, the climax vegetation for the Knolls Laboratory is eastern deciduous forest; only 7% of the site is forest. Then the forest can be examined to see whether any forest patches are large enough to be significant, whether these patches connect to other preserved similar habitats offsite, and whether there are corridors to offsite ecological resources.

Because the climax vegetation of a region usually protects the main threatened and endangered species, species assemblages (e.g., breeding frogs, neotropical migrants), and unique habitats (e.g., vernal ponds, Carolina bays), it is a good indicator of ecological health. Further, the intermix of habitats is often a key indicator for many species, and the intermix can be determined from the NLCD maps. Perhaps more importantly, the NLCD maps (and associated data) can be used to compare on-site with off-site resources, thereby, indicating whether the percentage of resources on site are regionally important. Even though a small site may have a small percentage of a given habitat or vegetation type, it can be significant regionally, and thus worthy for protection by the Site (in this case, DOE sites), aiding managers in making site decisions about future location of buildings or storage facilities. A visual inspection of maps can reveal whether the habitat is fragmented into small pieces.

In the above sections we have discussed the importance of maintaining ecological lands [14, 16-18]. This is often balanced against mission-related activities [45]. At some sites, wastes must be stabilized or stored on site [25, 37, 45]. Since one of the stated goals of DOE is to protect human health and the environment [37], DOE has an obligation to determine the best place to put waste disposal sites or engage in other remediation activities on site while still protecting valuable natural resources. We suggest an initial NLCD screening step is to determine whether the proposed site is on valuable ecological climax vegetation lands. By using the type of data presented in this paper DOE can determine whether the land cover of the proposed site is rare on-site. In other words, would destruction of the land cover (e.g., forest, grasslands) significantly decrease the amount of that habitat in the region? In general, the climax vegetation (the indicator examined in this paper) contains the valuable threatened and endangered species, and species of concern. This analysis can be completed with on-site data on land use/land cover.

A second level analysis is to determine how valuable the cover type on a proposed deposition site for hazardous materials might be to the local region. For example, at Paducah 34% is forest, while in the surrounding 10-km and 30-km bands it is only 17% and 24% respectively (refer to Table 2). One could argue that the forest on site is valuable, especially if the lands outside the site are vulnerable to further development (and therefore loss of climax forest). The maps generated by using the NLCD [26, 27] also provide visual information on connectivity of unique or important climax vegetation with the surrounding environment. For example, at Paducah the little remaining forest on-site is adjacent to off-site forest, increasing the ecological value of both (refer back to

Figure 5). The method we propose does not provide a solution, it provides the data for DOE, regulators and the public to decide how valuable a particular land cover type is. It can provide data to improve decision making.

Finally, land use/land cover data can be used to examine land use changes over time in DOE sites and surrounding communities, both with respect to ecological resources (e.g., climax vegetation), but also for development. Changes in percentage of development not only relate to loss of habitat for ecological receptors but can lead to changes in contaminants in surface and groundwater that will affect both ecological and human health [68-70]. At some DOE sites, for example, forests in large watershed can be assessed using the NLCD not only for the amount of forest, but for possible contamination routes with respect to facilities.

5.4.2 Societal

The NLCD method used in this paper provides stakeholders with an easy, transparent, and accessible method of examining current land use/land cover. The database is available to everyone and can thus serve as a basis for discussions about future use of land. Further, it is updated every 4-5 years, making it possible for agencies and the public to track changes over time. It is also quantitative and allows comparison with the surrounding region to determine if specific wild lands or green spaces on a site are important or critical for ecological reasons, and whether they are important for human health and well-being.

Considerations of any exposure from nuclear or chemical contaminants from any of these four sites must include terrestrial and aquatic biota, on- and off-site employees in the area, residents, and users of any adjacent rivers or streams [11]. For example, the Knolls Laboratory intersects with more than 100 m of Mohawk riverbank, allowing direct runoff from the site. In contrast, Paducah lies between several tributaries that flow into the Ohio River, again illustrating potential exposure pathways into large river systems [71, 72]. There is a possibility of seepage between groundwater, contaminated aquifers, and tributaries of major rivers [71]. The NLCD can aid agencies, organizations and the public with a tool to determine the percentage area coverage of waterways and wetlands. Additional maps identify nearby rivers that the tributaries from a site feed.

Direct exposure pathways of contaminants to humans or the environment are not the only societal effect of a site, whether contaminated or not. Disruptions or disturbances to intact ecosystems result in loss of biodiversity, and perhaps loss of goods and services such as walking, hiking, photography, collecting herbs or mushrooms, hunting, and fishing, among others [40]. Paducah has leased part of their wild, green spaces to the West Kentucky Wildlife Management Area on the edge of the Site, partly for conservation, ecological uses, wetlands, and watersheds [53]. Fishing and other recreational activities occur on this management area.

There are other, less tangible advantages to the presence of green space, however small. That is, specific open, green, or wild spaces on a site may not have an overarching ecological importance, but they may serve a human health need for open space that has been shown to lower the rates of several diseases [5, 6], including direct benefits to mental health and cardiovascular health, and lower mortality [7, 8]. Even the land use/land cover change itself can increase the risk from heart disease [73].

Being able to relatively quickly and accurately compare the land use/land cover types on-site and off-site, or among different sites, allows managers and communities to value the different uses on

site relative to the region and to enhance wild green spaces and ecological resources if it becomes clear they may be important regionally. Information on land use (development, agriculture) and land cover (forest, grasslands, desert) is particularly useful for DOE managers, community leaders, and the public for making future decisions about how to use the land based on the current presence of development and more undeveloped, wild lands. Managers and others concerned with remediation and reducing risks to workers and the public, as well as ecological systems, can form a clear, spatial picture of the resources on site. For example, are there forests or grasslands on site that deserve protection because they are large and continuous, in a healthy condition, and/or adjacent to other lands in the community? Collaboration with stakeholders is critical [74]. The information provided by the method allows for future land use planning considering current conditions and can be melded with information about the sources and possible transport of contaminants.

6. Conclusions

The process of determining whether there are valuable ecological resources on site is often costly and time-consuming, yet this information is essential to on-going management decisions. Often such facilities, such as DOE or other federal facilities, are obligated by law or regulation to protect human health and the environment. Usually, ecological evaluations are time-consuming, expensive and require trained personnel because they involve assessment of species, populations, and ecosystem health, as well as rare and unique species or habitats. The method described in this paper provides a reliable, relatively quick method of determining the percentage of different land use and land cover types on energy facilities (or other industrialized sites) using data from the U.S. National Land Cover Database. This database is available for the entire U.S., is available to everyone, and is updated every 3-5 years.

In the present study, land use/land cover of two sets of different-sized DOE sites were compared, indicating that the percent of development was higher for the smaller sites and illustrated the percentage of agriculture and wild areas on each site. Data and maps of each indicated differences in the placement of industrialized facilities on each site, and the location and connectedness of habitat patches. The land use/land cover types were also examined on a 10-km and 30-km buffer around each site. In all cases the data demonstrated significant differences between land use and land cover on the DOE sites with the surrounding 10-km and 30-km buffers. The presentation of both percentages and visual maps of the percentages of development, agriculture, and wild lands provides an information and communication tool that can be used by managers, regulators, and the public.

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Author Contributions

J.B. conceived, aided, directed the analysis, research, and wrote the first draft of the paper. M.G. aided in conception, analysis, and writing the paper. K.B. aided in conception, application of the

method to off-site resources, and editing. K.N. aided in compilation of data, graphics, and editing. D.K. aided in conception, development and editing.

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Competing Interests

There are no conflicts of interest reported by the author.

References

1. Hou D, Al-Tabbaa A. Sustainability: A new imperative in contaminated land remediation. *Environ Sci Policy*. 2014; 39: 25-34.
2. Brunner PH, Rechberger H. Waste to energy-key element for sustainable waste management. *Waste Manage*. 2015; 37: 3-12.
3. Crowley KD, Ahearne JF. Managing the environmental legacy of US nuclear-weapons production: Although the waste from America's arms buildup will never be "cleaned up", human and environmental risks can be reduced and managed. *Am Sci*. 2002; 90: 514-523.
4. Galvani AP, Bauch CT, Anand M, Singer BH, Levin SA. Human-environment interactions in population and ecosystem health. *Proc Natl Acad Sci*. 2016; 113: 14502-14506.
5. Kingsley M, Ontario E. Commentary climate change, health and green space co-benefits. *Health Promot Chronic Dis Prev Can*. 2019; 39: 131-135.
6. Akpinar A, Barbosa-Leiker C, Brooks KR. Does green space matter? Exploring relationships between green space type and health indicators. *Urban For Urban Green*. 2016; 20: 407-418.
7. Van den Berg M, Wendel-Vos W, van Poppel M, Kemper H, van Mechelen W, Maas J. Health benefits of green spaces in the living environment: A systematic review of epidemiological studies. *Urban For Urban Green*. 2015; 14: 806-816.
8. Sinnett D, Bray I, Baranyi G, Braubach M, Netanyahu S. Systematic review of the health and equity impacts of remediation and redevelopment of contaminated sites. *Int J Environ Res Public Health*. 2022; 19: 5278.
9. Centers for Disease Control and Prevention. About one health [Internet]. Atlanta, GA: Centers for Disease Control and Prevention; 2025. Available from: <https://www.cdc.gov/one-health/about/index.html>.
10. U.S. Environmental Protection Agency. Cleaning up the Nation's waste sites markets and technology trends [Internet]. Washington, D.C.: U.S. Environmental Protection Agency; 2004. Available from: <https://nepis.epa.gov/Exe/ZyNET.exe/300061I3.TXT?ZyActionD=ZyDocument&Client=EPA&Index=2000+Thru+2005&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0>

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11. U.S. Environmental Protection Agency. Ecoregions of North America [Internet]. Washington, D.C.: U.S. Environmental Protection Agency; 2025. Available from: <https://www.epa.gov/eco-research/ecoregions-north-america>.
12. U.S. Environmental Protection Agency. EJSCREEN: Environmental Justice Mapping and Screening Tool [Internet]. Washington, D.C.: U.S. Environmental Protection Agency; 2024. Available from: <https://www.epa.gov/system/files/documents/2024-07/ejscreen-tech-doc-version-2-3.pdf>.
13. Davidson MD. On the relation between ecosystem services, intrinsic value, existence value and economic valuation. *Ecol Econ*. 2013; 95: 171-177.
14. Department of Energy. Stewards of national resources. Washington, D.C.: Office of Energy Research, Department of Energy; 1994; DOE/FM-0002.
15. Department of Energy. National Environmental Research Parks [Internet]. Washington, D.C.: U.S. Department of Energy; 1994. Available from: <https://www.osti.gov/servlets/purl/10161197-zAKh41/native/>.
16. Brown KS. The great DOE land rush? *Science*. 1998; 282: 616-617.
17. Dale VH, Parr PD. Preserving DOE's research parks. *Issues Sci Technol*. 1997; 14: 73-77.
18. Whicker FW, Hinton TG, MacDonell MM, Pinder III JE, Habegger LJ. Avoiding destructive remediation at DOE sites. *Science*. 2004; 303: 1615-1616.
19. Burger J, Gochfeld M. Consistency and local adaptation in use of ecological and eco-cultural indicators: Assessing risk from contamination. *J Risk Res*. 2022; 25: 911-939.
20. Burger J. Bioindicators: A review of their use in the environmental literature 1970-2005. *Environ Bioindic*. 2006; 1: 136-144.
21. Burger J. Stakeholders and scientists: Achieving implementable solutions to energy and environmental issues. New York, NY: Springer Science & Business Media; 2011.
22. Burger J. A framework for increasing sustainability and reducing risk to ecological resources through integration of remediation planning and implementation. *Environ Res*. 2019; 172: 586-595.
23. National Academies of Sciences, Medicine, Division on Earth, Life Studies, Radiation Studies Board, Committee on Independent Assessment of Science, Technology for the Department of Energy's Defense Environmental Cleanup Program. Independent assessment of science and technology for the Department of Energy's defense environmental cleanup program. Washington, D.C.: National Academies Press; 2019.
24. Department of Energy. Charting the course: The future use report [Internet]. Washington, D.C.: U.S. Department of Energy; 1996. Available from: <https://babel.hathitrust.org/cgi/pt?id=uiug.30112003744569&seq=1>.
25. Department of Energy. A Review of the Environmental Management Program (Presented by the Top-to-Bottom Review Team) [Internet]. Washington, D.C.: U.S. Department of Energy; 2002. Available from: <https://www.energy.gov/em/articles/review-environmental-management-program-presented-top-bottom-review-team>.

26. National Land Cover Database. National Land Cover Database (NLCD) 2016 [Internet]. Sioux Falls, SD: Multi-Resolution Land Characteristics; 2016. Available from: <https://www.mrlc.gov/national-land-cover-database-nlcd-2016>.
27. National Land Cover Database. National Land Cover Database 2021 (NLCD2021) Statistics for 2021 [Internet]. Sioux Falls, SD: Multi-Resolution Land Characteristics; 2021. Available from: <https://www.mrlc.gov/data/statistics/national-land-cover-database-2021-nlcd2021-statistics-2021>.
28. Burger J, Gocheld M, Kosson D, Brown KG, Cortes M. Development of a method to evaluate ecological risk: Oak ridge reservation as a case study-22313 [Internet]. Vienna, Austria: International Atomic Energy Agency; 2022. Available from: <https://inis.iaea.org/records/nevx6-97925>.
29. Burger J, Gochfeld M, Giffen N, Brown KG, Cortes M, Ng K, et al. Comparing land cover and interior forests on contaminated land and the surrounding region: Oak Ridge Reservation as a case study. J Toxicol Environ Health A. 2023; 86: 501-517.
30. Burger J, Gochfeld M, Brown KG, Cortes M, Ng K, Kosson D. Using the National Land Cover Database as an indicator of shrub-steppe habitat: Comparing two large United States federal lands with surrounding regions. J Toxicol Environ Health A. 2025; 88: 1-19.
31. U.S. Environmental Protection Agency. Land use in CERCLA remedy selection process [Internet]. Washington, D.C.: U.S. Environmental Protection Agency; 1995. Available from: <https://www.epa.gov/sites/default/files/documents/landuse.pdf>.
32. U.S. Environmental Protection Agency. Ecological Risk Assessment Guidance for Superfund: Process for Designing and Conducting Ecological Risk Assessments. Interim Final [Internet]. Washington, D.C.: U.S. Environmental Protection Agency; 1997. Available from: <https://semspub.epa.gov/work/11/157941.pdf>.
33. U.S. Environmental Protection Agency. A Guide to Preparing Superfund Proposed Plans, Records of Decision, and Other Remedy Selection Decision Documents [Internet]. Washington, D.C.: U.S. Environmental Protection Agency; 1999. Available from: <https://semspub.epa.gov/work/05/417125.pdf>.
34. Gephart RE. A short history of waste management at the Hanford Site. Phys Chem Earth A/B/C. 2010; 35: 298-306.
35. Energy Communities Alliance. Oak Ridge Reservation [Internet]. Washington, D.C.: Energy Communities Alliance; 2026. Available from: <https://www.energyca.org/site-profiles/oak-ridge-reservation>.
36. Department of Defense. Coming in from the Cold: Military Heritage in the Cold War: Report on the Department of Defense Legacy Cold War Project. Ann Arbor, MI: University of Michigan Library; 1994. Available from: <https://babel.hathitrust.org/cgi/pt?id=mdp.39015032277280&seq=1>.
37. Department of Energy. Cleanup Sites [Internet]. Washington, D.C.: U.S. Department of Energy; 2025. Available from: <https://www.energy.gov/orem/cleanup-sites>.
38. Department of Energy. Hanford lifecycle scope, schedule, and cost report [Internet]. Washington, D.C.: U.S. Department of Energy; 2019. Available from: https://www.hanford.gov/files.cfm/2019_Hanford_Lifecycle_Report_w-Transmittal_Letter.pdf.

39. Lamb EG, Bayne E, Holloway G, Schieck J, Boutin S, Herbers J, et al. Indices for monitoring biodiversity change: Are some more effective than others? *Ecol Indic.* 2009; 9: 432-444.
40. Costanza R, De Groot R, Sutton P, Van der Ploeg S, Anderson SJ, Kubiszewski I, et al. Changes in the global value of ecosystem services. *Global Environ Change.* 2014; 26: 152-158.
41. Costanza R, De Groot R, Braat L, Kubiszewski I, Fioramonti L, Sutton P, et al. Twenty years of ecosystem services: How far have we come and how far do we still need to go? *Ecosyst Serv.* 2017; 28: 1-16.
42. Cairns Jr J. Rehabilitating damaged ecosystems. 2nd ed. Boca Raton, FL: CRC Press; 1995.
43. Forman RTT. Land mosaics: The ecology of landscapes and regions. Cambridge, UK: Cambridge University Press; 1995.
44. U.S. Environmental Protection Agency. Hazardous Waste Cleanup: USDOE Knolls Atomic Power Laboratory in Niskayuna, New York [Internet]. Washington, D.C.: U.S. Environmental Protection Agency; 2026. Available from: <https://www.epa.gov/hwcorrectiveactioncleanups/hazardous-waste-cleanup-usdoe-knolls-atomic-power-laboratory-niskayuna>.
45. Department of Energy. EM Strategic Vision: 2024-2034 [Internet]. Washington, D.C.: U.S. Department of Energy; 2024. Available from: <https://www.energy.gov/sites/default/files/2024-03/DOE%20EM%20Strategic%20Vision%202024%20FINAL%20sm.pdf>.
46. Department of Energy. Environmental monitoring report - Knolls Laboratory and Kesselring Site - Calendar Year 2022 [Internet]. Washington, D.C.: U.S. Department of Energy; 2022. Available from: <https://navalnuclearlab.energy.gov/nnl-assets/2024/01/Knolls-Laboratory-and-Kesselring-Site-EMR-pt1.pdf>.
47. Department of Energy. Management of Process Contaminated Soils within T&D Activities at LLNL [Internet]. Washington, D.C.: U.S. Department of Energy; 2025. Available from: <https://www.osti.gov/servlets/purl/2544440>.
48. Department of Energy. 2023 Annual Site Environmental Report [Internet]. Washington, D.C.: U.S. Department of Energy; 2024. Available from: <https://www.energy.gov/sites/default/files/2024-10/2023%20ASER%2009-2024%20-%20signed.pdf>.
49. Department of Energy. Environmental Monitoring Plan Fiscal Year 2025 Paducah Gaseous Diffusion Plant, Paducah Kentucky [Internet]. Washington, D.C.: U.S. Department of Energy; 2024. Available from: <https://pubdocs.pad.pppo.gov/Environmental%20Monitoring%20Plan%20%28EMP%29/EMP%202025/EMP%20FY%202025.pdf>.
50. Costella M, Lind S, Schweickert D, Hancock R, Felish A, Mertesdorf E. Management of process contaminated soil within T & D activities at LANL. Proceedings of the Waste Management Symposia 2025; 2025 March 13; Phoenix, AZ, USA. Livermore, CA: Lawrence Livermore National Laboratory.
51. Department of Energy. 2023 Paducah Annual Site Environmental Report [Internet]. Washington, D.C.: U.S. Department of Energy; 2024. Available from: <https://www.energy.gov/pppo/articles/2023-paducah-annual-site-environmental-report>.
52. Department of Energy. Study to Guide Paducah Site Reindustrialization Nears Completion [Internet]. Washington, D.C.: U.S. Department of Energy; 2025. Available from:

<https://www.energy.gov/em/articles/study-guide-paducah-site-reindustrialization-nears-completion>.

53. Department of Energy. Paducah 2008 land use plan. Washington, D.C.: Department of Energy; 2008; DOE/LX/07-1256&D2.
54. Department of Energy. 2023 Portsmouth site annual site environmental report [Internet]. Washington, D.C.: U.S. Department of Energy; 2024. Available from: <https://www.energy.gov/media/338361>.
55. Wiley R, Conley G, Porter S, Simon D, Kruse N, Eichenberg R, et al. Habitat Mapping of the Land and Vicinity of the United States Department of Energy (DOE) Portsmouth Gaseous Diffusion Plant (PORTS) Pike County, Ohio [Internet]. Athens, OH: Ohio University; 2019. Available from: https://www.sodidevelopment.org/wp-content/uploads/2019/06/PORTS_Habitat_Report.pdf.
56. U.S. Department of the Interior, U.S. Geological Survey. A Sagebrush Conservation Design to Proactively Restore America's Sagebrush Biome [Internet]. Reston, VA: U.S. Geological Survey; 2022. Available from: <https://pubs.usgs.gov/of/2022/1081/ofr20221081.pdf>.
57. Applestein C, Germino MJ. Patterns of post-fire invasion of semiarid shrub-steppe reveals a diversity of invasion niches within an exotic annual grass community. *Biol Invasions*. 2022; 24: 741-759.
58. SAS Institute Inc. SAS/STAT 15.1 User's Guide [Internet]. Cary, NC: SAS Institute Inc. Available from: https://documentation.sas.com/doc/zh-CN/pgmsascdc/9.4_3.4/statug/titlepage.htm.
59. McDonald JH. Fisher's exact test of independence. In: *Handbook of Biological Statistics*. Baltimore, MD: Sparky House Publishing; 2015. pp. 77-85. Available from: <http://www.biostat handbook.com/fishers.html>.
60. Anderson JL, Apostoaei AI, Yiin JH, Tseng CY. Exposure to recycled uranium contaminants in gaseous diffusion plants. *Radiat Prot Dosimetry*. 2017; 175: 503-507.
61. Yiin JH, Anderson JL, Bertke SJ, Tollerud DJ. Dose-response relationships between internally-deposited uranium and select health outcomes in gaseous diffusion plant workers, 1948-2011. *Am J Ind Med*. 2018; 61: 605-614.
62. Yu S, Halbrook RS, Sparling DW, Colombo R. Metal accumulation and evaluation of effects in a freshwater turtle. *Ecotoxicology*. 2011; 20: 1801-1812.
63. Yu S, Halbrook RS, Sparling DW. Correlation between heavy metals and turtle abundance in ponds near the Paducah Gaseous Diffusion Plant, Kentucky, USA. *Arch Environ Contam Toxicol*. 2013; 65: 555-566.
64. Kroodsma RL. Effect of edge on breeding forest bird species. *Wilson Bull*. 1984; 96: 426-436.
65. Fischer J, Lindenmayer DB. Landscape modification and habitat fragmentation: A synthesis. *Global Ecol Biogeogr*. 2007; 16: 265-280.
66. Riitters K, Wickham J, O'Neill R, Jones B, Smith E. Global-scale patterns of forest fragmentation. *Conserv Ecol*. 2000; 4. Available from: <https://ecologyandsociety.org/vol4/iss2/art3/>.
67. Poodat F, Arrowsmith C, Fraser D, Gordon A. Prioritizing urban habitats for connectivity conservation: Integrating centrality and ecological metrics. *Environ Manage*. 2015; 56: 664-674.
68. Prashanth M, Kumar A, Dhar S, Verma O, Rai SK, Kouser B. Land use/land cover change and its implication on soil erosion in an ecologically sensitive Himachal Himalayan watershed, Northern India. *Front For Glob Change*. 2023; 6: 1124677.

69. Verma O, Kouser B, Khosla A, Kumar R. Evaluation of groundwater quality for drinking and irrigation purposes, ionic sources and land use/land cover impacts in the Kathua region of Jammu and Kashmir, India. *Groundw Sustain Dev*. 2024; 26: 101303.
70. Kouser B, Verma O. Health risk assessment of groundwater contamination in the Union Territory of Jammu and Kashmir, northern India. *Curr Opin Environ Sci Health*. 2024; 42: 100585.
71. Fryar AE, Wallin EJ, Brown DL. Spatial and temporal variability in seepage between a contaminated aquifer and tributaries to the Ohio River. *Groundwater Monit Rem*. 2000; 20: 129-146.
72. DeGarady CJ, Halbrook RS. Using anurans as bioindicators of PCB contaminated streams. *J Herpetol*. 2006; 40: 127-130.
73. Schmidt CW. Land-use changes and heart disease risk: Evidence that rapid development plays a role. *Environ Health Perspect*. 2020; 128: 094004.
74. Renn O. Stakeholder and public involvement in risk governance. *Int J Disaster Risk Sci*. 2015; 6: 8-20.