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CONTRIBUTED PAPER

Conservation value of national forest roadless areas

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Abstract

Conservation scientists call for establishing additional protected areas amidst ongoing threats of expanding human development. Nevertheless, some existing protected areas are being downsized and demoted of their existing conservation protections. In 2001, the Roadless Area Conservation Rule prohibited road construction and timber harvest in 240,000 km^2 of inventoried roadless areas (IRAs) located on United States Department of Agriculture Forest Service lands. IRAs represent a non-legislative protected status that is in jeopardy of conservation demotion or "degazettement," and few national protected area assessments recognize the IRA designation. Since the rule's conception two decades ago, little research has been conducted to assess the conservation values of IRAs and the values they could add to the existing system of highly protected areas in the continental United States. To increase understanding of these conservation values, we assessed three aspects of roadless areas: (a) how wild and intact are IRA lands compared to state, national, and protected lands, (b) how do IRAs complement the size, connectedness, and representation of protected lands, and (c) how do IRAs contribute to protection of important ecosystem services (drinking water and annual carbon capture)? Through this analysis we found that many IRAs are among the most wild, undeveloped areas both in the nation and within their respective states. IRAs increase the size of—and reduce isolation between—protected areas, likely buffering them from external stressors. In some places, IRAs protect watersheds that deliver drinking water to hundreds of thousands of people. IRAs also add significantly to the total carbon captured by existing protected areas. The results of our evaluation demonstrate the potential of IRAs to contribute to the conservation value of the U.S. protected area system and to deliver important ecosystem services.

KEYWORDS

buffers, conservation reserves, drinking water, ecosystem services, inventoried roadless areas, protected areas, Roadless Rule

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1 | INTRODUCTION

The ecological effects of roads and their related impacts include fragmenting habitat, providing vectors for invasive species, and degrading water quality, among others (Trombulak & Frissell, 2000). While much of the terrestrial Earth is roadless (Ibisch et al., 2016), roadless areas are disproportionately rare inside of the contiguous U.S. (Watts et al., 2007). Associated with the global expansion of road networks, terrestrial ecosystems that are relatively free of human modification (e.g., "wildlands") are being lost to development at nearly twice the rate of their protection (Watson et al., 2016). Additionally, the western United States lost nearly 12,000 km^2 (3 million acres) of open and natural land to development in the decade following 2001 (Theobald, Leinwand, Anderson, Landau, & Dickson, 2019). In response, ecologists have stressed the importance of protecting what is left of the remaining wild places (Belote et al., 2017; Martin, Maris, & Simberloff, 2016; Watson et al., 2018).

In January 2001, recognizing the value of roadless areas, the US Department of Agriculture (USDA) Forest Service established the Roadless Area Conservation Rule, which recognized Inventoried Roadless Areas (IRAs), areas that the agency had identified, inventoried, and found to be free of roads in the 1970s, and prohibited road construction and timber harvest within them in 37 states within the contiguous U.S. (the Rule also covered Alaska, which is not considered here). The primary goal of this policy is to sustain the health and productivity of America's forests so present and future generations can benefit from the resources they offer, but the Rule is also intended to address Forest Service concerns with its ability, due to budget constraints, to maintain the vast amount of existing roads to the environmental standards required by law. Lacking roads and human-infrastructure, IRAs represent relatively wild and undeveloped land, but their potential contribution to the nation's protected area system has not been assessed (but see Aplet, Wilbert, & Morton, 2005).

Because IRAs are an administrative designation of the U.S. Forest Service and not legislatively established by the U.S. Congress, IRAs are not considered part of the U.S. system of protected areas (i.e., units classified with a Gap Analysis Program [GAP] status of 1 or 2) in protected areas databases of the U.S. (USGS GAP, 2012). Protected areas classified as GAP 1 or 2 are governed by mandates to maintain biodiversity, prohibit land cover conversion, and minimize other human stressors. Road building and commercial timber harvesting are prohibited in IRAs, but livestock grazing, motorized recreation, and some mining is permitted. While IRAs provide similar levels of protection to many GAP 1 and 2 areas, their administrative status leaves them vulnerable to efforts to repeal the Roadless Rule completely, as occurred recently in Alaska and Utah (see Weber, 2019). These calls to downgrade the levels of protection from IRAs mirror similar threats to eliminate or reduce the size of other protected areas (Golden Kroner et al., 2019).

Elimination of conservation protections has occurred despite ongoing calls to protect more land to address the growing biodiversity crisis (Aycrigg et al., 2016; Convention on Biological Diversity, 2014; Dinerstein et al., 2019; Jenkins, Van Houtan, Pimm, & Sexton, 2015; Watson et al., 2016). In addition, to facilitate adaptation to a changing climate, conservation scientists have recommended protecting the last remaining wild lands (Watson et al., 2018), connecting existing reserves (Belote et al., 2016), and more fully representing ecological diversity within the protected area system (Aycrigg et al., 2013). Growing the protected area system is also seen as necessary to sustain important ecosystem services upon which humans depend (Dinerstein et al., 2019; Jarvis, 2020).

IRAs are not recognized as formal protected areas but likely represent an example of "other effective area-based conservation measures" (OECMs; IUCN-WCPA, 2019). OECMs are lands not classified as protected but which are "governed and managed in ways that achieve positive and sustained long-term outcomes for the in situ conservation of biodiversity with associated ecosystem functions…" (IUCN-WCPA, 2019). OECMs may also contribute to the ecological representation and connectivity of protected areas. Documenting the role of OECMs is critical to fully account for the contribution to conservation.

Considering the lack of formal recognition that IRAs receive as protected areas, recent calls to repeal the Roadless Rule (Weber, 2019), and ongoing threats to reduce or eliminate protected areas, we undertook an assessment of the potential contributions of IRAs to the protected area system of the contiguous U.S. We focus on three guiding questions throughout the study: (a) How might IRAs add to the protection of the wildest lands in the contiguous U.S. and respective states? (b) How do IRAs contribute to the size, connectedness, and representation of protected areas? (c) How do IRAs add to the ability of protected areas to deliver ecosystem services of drinking water protection and carbon capture?

2 | METHODS

To compare IRAs with currently protected areas in the contiguous United States, we define protected areas as lands designated within the Gap Analysis Program's Protected Areas Database version 10.3 (USGS GAP, 2012) with GAP 1 and 2 status, excluding national fisheries and marine sanctuaries. These protected areas are mostly composed of lands managed by federal and state agencies to maintain biodiversity and limit resource extraction, though private easements are also included as GAP 1 and 2 when their management prevents land use conversion and aims to protect biodiversity. We considered GAP 1 and 2 areas that shared borders as one protected core area. To create cores, we dissolved boundaries of all protected areas directly adjacent to one another. For instance, Yellowstone National Park and the adjacent wilderness areas were treated as one protected core area in our data set. For our analysis, we included 92,556 protected core areas representing 602,901 km^2 (ranging in size from <1 to 24,040 km^2).

Within the IRA database, some IRAs overlap with currently protected GAP 1 and 2 lands. For this analysis, we removed any sections of IRA land that overlap GAP status 1 and 2 lands from the IRA database and assigned those areas to GAP 1 and 2. These areas of overlap between GAP 1 and 2 lands and IRAs occurred mostly in Wilderness Study Areas and represented 4.7% of the total IRA area. IRAs with the same name but delineated by either North, South, East or West, or by sections (A, B, C, etc.) were combined to make up a single IRA spatial unit.

2.1 | IRAs and wildness

To measure wildness, we used existing spatial data on the degree of human modification (Theobald, 2013) but reverse-ordered the data so that higher values are associated with "wilder" (i.e., less human-modified) lands. Human modification was quantified using data on roads, railways, transmission lines, land cover, and human population density (see Theobald, 2013 for more details). The human modification map is closely correlated with earlier maps of wildness (Aplet, Thomson, & Wilbert, 2000) and has been used in recent research to identify the wildest lands in the lower 48 US states (Belote et al., 2017). In order to compare wildness between IRAs and protected areas, we extracted all wildness values across each designation. We then classified wildness values into deciles based on the distribution across the contiguous US and assigned each decile an integer 1 (lowest decile) through 10 (highest decile). We classified the data in this way to more clearly evaluate how much of the wildest lands were protected in GAP 1 and 2 lands and how IRAs might contribute to protecting the wildest lands.

We also extracted mean wildness for all IRAs and compared them with wildness values within their respective states as well as wildness values across the contiguous US. This allowed us to compare the mean wildness of IRAs to the state-wide and full national distribution of gradients in wildness.

2.2 | IRAs and the size of protected areas

To determine how IRAs contribute to the size of protected areas, we calculated total area of protected lands (GAP 1 and 2 lands excluding national fisheries and marine sanctuaries), as well as the total area contained within IRAs. We also analyzed how IRAs effectively increase the size of protected areas by locating all IRAs directly adjacent to existing protected areas. We then compared the area of the protected system as it stands today to what it would be with the inclusion of these IRAs. We also analyzed how IRAs adjacent to individual protected core areas would increase the size of those cores. We spatially joined the protected core areas to adjacent IRAs. We then summed the area of IRAs adjacent to each core and compared the area of cores before and after the spatial join by calculating the percent and absolute increase in area of each protected core after adding adjacent IRAs.

Following this analysis and after looking at the maps of IRAs and their locations with respect to protected lands, we noticed that some IRAs appear to form larger land unit complexes with protected areas at their core with adjacent IRAs (identified above) and additional IRAs very close to those. These complexes may form large intact and relatively connected core areas for maintaining wildlife movement (Gaston, Jackson, Cantú-Salazar, & Cruz-Piñón, 2008; Tucker et al., 2018). To analyze the extent to which IRAs may create complexes with core protected areas in this way, we selected all IRAs within 100 m of a protected area and joined them to protected areas (Step 1). Then, we selected all IRAs within 100 m of the layer created in Step 1 and continued this stepped process until no IRAs were within 100 m of the previous step. In addition to the 100-m distance, we repeated the analysis using 5 and 10 km stepped build out distances to account for wide ranges in animal dispersal distances (Bowman, Jaeger, & Fahrig, 2002).

2.3 | IRAs and ecological representation

We were interested in whether IRAs contained ecosystems not otherwise well-protected in existing protected areas. We relied on the GAP national land cover data set

(USGS, 30-m resolution) to evaluate ecological representation of protected areas and IRAs (Aycrigg et al., 2013, 2016; Dietz, Belote, Aplet, & Aycrigg, 2015). We extracted landcover data within protected areas, as well as protected areas with the inclusion of IRAs to calculate increase in representation. We focused on the "formation" ($n = 31$) level of ecosystem classification to summarize results, as it provided a sufficiently detailed yet tractable number of classes in the hierarchy of national vegetation classification. We removed human-altered land cover formations from our assessment, including: Current and Historic Mining Activity, Developed and Urban, Introduced and Semi Natural Vegetation, Open Water, Pasture and Hay Field Crop, Recently Disturbed or Modified, Row and Close Grain Crop Cultural Formation, and Woody Horticultural Crop. We assessed which formations were located in protected areas and IRAs, and we used the percentage of each as a measure of ecological representation within the lower 48 United States.

2.4 | IRAs and ecosystem services

Potential importance of IRAs for drinking water supply was assessed by examining the percentage of IRAs that were also surface water and groundwater protection areas (henceforth referred to as drinking water protection areas or DWPAs) as delineated by the US Environmental Protection Agency (U.S. Environmental Protection Agency, 2017). A water protection area is defined as all US Geological Survey National Hydrography Dataset plus catchments located 1 day's water time of travel (24 hr) upstream from a surface water intake or groundwater facility point. Drinking water protection areas were calculated for all active systems and surface water facilities (i.e., intakes, reservoirs, infiltration galleries, and springs) and groundwater facilities (i.e., wells) with valid spatial locations as of July 2017. Percent DWPA area was calculated by dividing the 12-digit Hydrologic Unit Code (HUC12) area located within a DWPA by the total area of the HUC12. Exact locations of drinking water facilities or DWPAs are not included in the data set. To determine how the addition of IRAs to the protected area network would increase protection of important watersheds, we first performed an intersection of GAP 1 and 2 lands and all HUC12 watersheds that touch NFS lands. From these data, we calculated the percentage of each watershed that was covered by GAP 1 and 2 lands. The overall percentage of DWPA was then compared against the percentage of the watershed covered by GAP 1 and 2 lands to examine potential importance of these protected lands to drinking water supplies. In order to assess how adding IRAs to the protected area network could aid in preserving water quality in the lower 48, we then merged the IRA shapefile with the GAP 1 and 2 shapefile and repeated the steps above. Related tables for each HUC12 watershed detail the water providers served by the watershed. These water-provider data include the total population served as reported by the water-providers to the USEPA.

We quantified carbon capture of existing protected areas and IRAs using an estimate of net primary productivity (NPP, g C m^{-2} yr^{-1}) provided by the Numerical Terradynamic Simulation Group at the University of Montana. NPP data represent the average annual estimates from the years 2000 to 2012 at 1-km resolution (method describe in Zhao, Heinsch, Nemani, & Running, 2005). We converted the original raster units (g C m^{-2} yr^{-1}) to kg C km^{-2} yr^{-1} to stay consistent with the 1-km resolution. We then extracted and summed NPP data for protected areas and IRAs to quantify how much more annual carbon fixation IRAs might contribute to protected areas (reporting values as total Mg of carbon per year for all protected areas and IRAs). Protected areas and IRAs <1 km^2 were removed from this analysis to ensure NPP estimates were based on at least one full pixel value. Excluding these small units removed only 1.1% of the total area from protected cores and 0.01% area from IRAs. We then stratified the contiguous U.S. into three regions (west, interior west, and east) to evaluate how the contribution of IRAs to protected area carbon capture varies across these broad regions. The West included California, Oregon, and Washington. The Interior West included Idaho, Nevada, Utah, Arizona, Montana, Wyoming, Colorado, New Mexico, North and South Dakota, Nebraska, Kansas, Oklahoma, and Texas. The East included all other contiguous states. As an ancillary analysis, we calculated the average elevation of IRAs and protected areas.

3 | RESULTS

3.1 | IRAs and wildness

Currently, protected areas (GAP 1 and 2 lands excluding national fisheries and marine sanctuaries) encompass 602,901 km^2 of land within the contiguous U.S., representing 8% of land area, and IRAs account for another 2% (161,708 km^2) (Table 1). Despite their relatively small area, GAP 1 and 2 lands protect some of the wildest places in the contiguous U.S., including 24% (195,025 km^2) of the top 10% wildest lands in the contiguous U.S. IRAs, if added to the conservation network, would increase that amount to 31%. Furthermore, if all IRAs were added to the protected network, nearly

TABLE 1 The table below displays protected area (GAP 1 and 2) area and the amount and percent of IRA land directly adjacent to a protected area, as well as IRA area within 100 m, 5 km, and 10 km of a protected area

Description	Area (km^2)	Percentage of all IRA area	Percentage increase in PA area
Protected areas	602,901		
Adjacent IRAs	93,818	58%	15.6%
IRAs within 100m of a protected area	99,448	61%	16.5%
IRAs within 5km of a protected area	135,906	84%	22.5%
IRAs within 10km of a protected area	149,899	93%	24.9%
All IRAs	161,708	100%	26.8%

115,000 km^2 of the top 20% wildest places in the lower 48 would be added to conservation reserves (Figure 1).

Ninety-six percent of IRAs are wilder than the median value for the contiguous U.S. (i.e., the majority of IRAs are among the wildest half) (Supplemental S1 and S2). Additionally, 21% of IRAs are in the top 10% of wildest places in the lower 48, while 8% of IRAs are in the top 5%. In some states, IRAs considered relatively wild at the national level are overshadowed by the abundance of wild lands at the state level. For example, Idaho

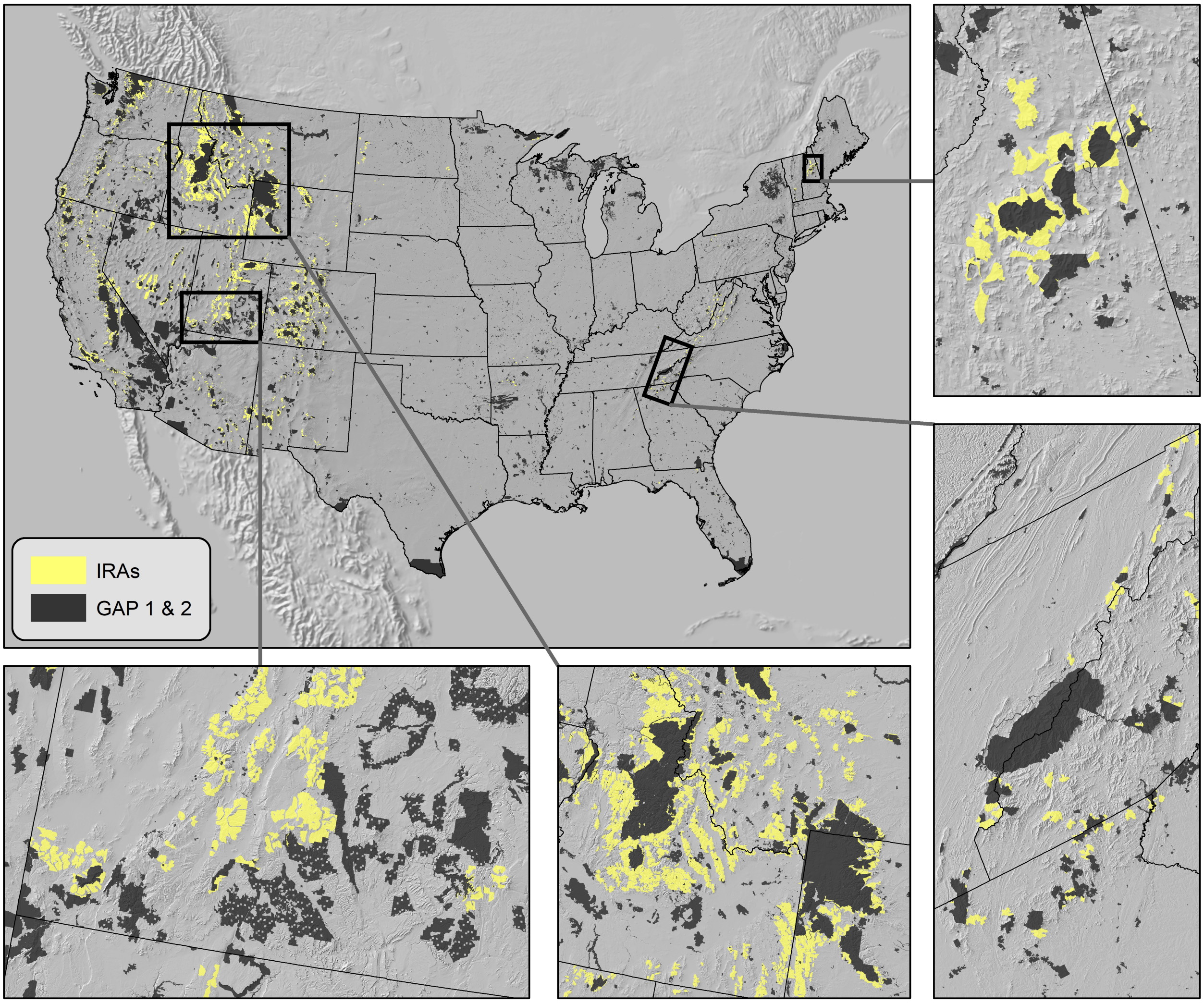

FIGURE 1 Map of protected areas (GAP 1 and 2 lands, black) and USDA Forest Service Inventoried Roadless Areas (yellow)

has 52 IRAs in the top 5% wildest places in the contiguous U.S. but not a single IRA in the top 10% wildest places in the state. Alternatively, Virginia has six IRAs in the top 5% wildest places in the state, but not a single IRA in the top 25% wildest places in the contiguous U.S. These patterns provide statewide and national context for the relative wildness of IRAs.

3.2 | IRAs and the size of protected areas

As described above, the protected area system of the contiguous U.S. currently includes 602,901 km^2. Incorporating IRAs in that system increases its total area by 27% to 764,609 km^2. Across the contiguous U.S., 1,127 IRAs are directly adjacent to a protected core, increasing the size of protected cores by 93,818 km^2 or 15.6% (Table 1). In fact, 6 of the top 10 largest protected cores have adjacent IRAs, which on average add 25% to their total area (Table 2). In some cases, very small conservation easements adjacent to IRAs could increase their size by three orders of magnitude relative to their size without including IRAs. In many cases, IRAs are not immediately adjacent to protected cores but add substantially to the distributed protected area system within a region (e.g., southern Utah and the Southern Appalachians in Figure 2). In all, 149,899 km^2 of IRAs (93% of IRA area) lie within 10 km of a protected core (Table 1).

While 93,818 km^2 of IRAs are directly adjacent to protected areas, an additional 5,630 km^2 are within 100-m of a protected area, and 14,091 km^2 more are within 100 m of those IRAs (Figure 3). If one were to continue building out from IRAs within 100 m of each other, 120,159 km^2 of IRA land would be connected to a protected area via a network of proximal units. With the inclusion of IRAs within this 100-m build-out system, the amount of land within the protected network would increase from 602,901 to 723,059 km^2. Based on the build-out steps using a 5-km threshold between edges, the amount of land in the protected system would increase to 758,039 km^2. Finally, at the 10-km threshold, the amount of protected land would increase to 761,815 km^2 (Figure 3).

TABLE 2 The 10 largest protected core areas determined after combining adjacent Gap 1 and 2 units with shared borders

Core area	Largest protected area	Size of the largest protected area (km^2)	Size of core area (km^2)	Size of adjacent IRAs (km^2)	Percent increase with IRAs included
Greater Yellowstone	Yellowstone National Park	8,900	24,040	6,878	29
Central Idaho	Frank Church-River of No Return Wilderness	9,579	17,633	6,767	38
Death Valley	Death Valley National Park	13,649	16,421	231	1
South Sierra	Yosemite National Park	3,028	13,605	2,337	17
Mojave Desert	Mojave Wilderness	2,813	12,839	0	NA
Lower Rio Grande[a]	Laguna Atascosa National Wildlife Refuge	183	12,725	0	NA
Crown of the Continent	Bob Marshall Wilderness	4,301	10,490	3,373	32
North Cascades	North Cascades National Park	2028	9,548	2,921	31
Desert National Wildlife Refuge	Desert National Wildlife Refuge	6,540	8,990	0	NA
Everglades	Everglades National Park	6,227	7,013	0	NA

Note: Here we name the core area, the largest protected area within these cores, the size of the largest protected area, the size of the entire core area, size of adjacent IRAs, and percent increase in area when IRAs are added to the cores. Six of these largest core areas included adjacent IRAs expanding the total area by an average of 25%. In these cases, IRAs likely serve as key buffers around core protected areas.

[a] The Protected Areas Database (PAD) includes a large GAP 2 "protected area" in the southern tip of Texas, which we include here for the sake of consistency with the PAD, but the area consists mostly of as-yet unprotected private land within the purchase area boundary of the Lower Rio Grande National Wildlife Refuge, which, at this time, is smaller than the nearby Laguna Atacosa NWR adjacent to the purchase area.

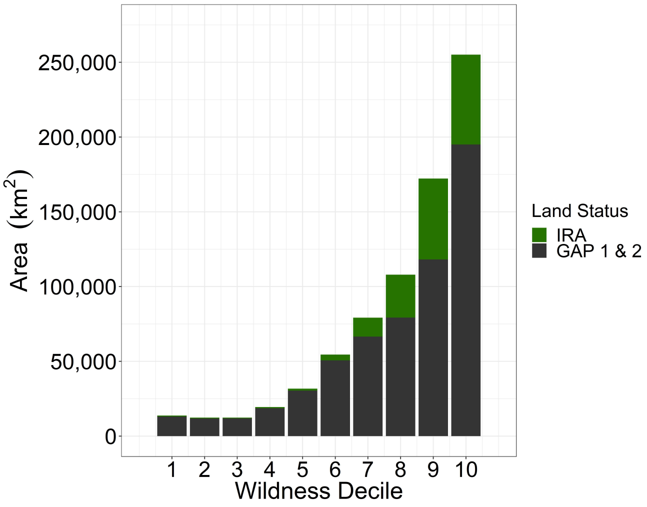

FIGURE 2 Comparison of wildness values within IRAs (green) and protected lands (grey). Values are binned by deciles of all wildness values in the lower 48, for example, the last bar represents GAP 1 and 2 and IRA lands in the top 10% wildest places in the lower 48

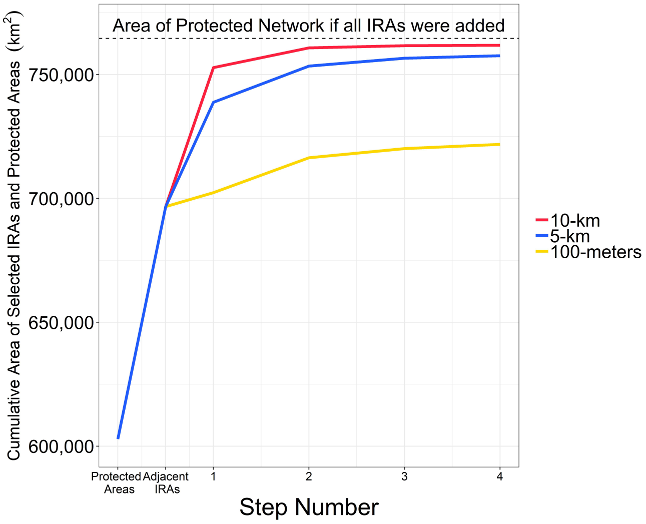

FIGURE 3 Cumulative area within the protected network with the inclusion of IRA stepping stones at 100-m, 5-, and 10-km increments. If IRAs within 10-km of a protected network were included in the protected network, as well as IRAs within 10-km of those IRAs and so on, the protected network would increase in size from 600,000 to over 750,000 km^2. See Table 2 for step descriptions

3.3 | IRAs and ecological representation

By far, the most common "formation" in the protected area system is Cool Temperate Forest and Woodland, representing 40.6% of GAP 1and 2 vegetation, followed by Cool Semi-Desert Scrub and Grassland (17.8%) and Warm Desert and Semi-Desert Scrub and Grassland (13.5%), which together account for over 70% of protected area vegetation (Table 3). The composition of IRAs is even more tilted toward Cool Temperate Forest and Woodland (67.0%) and Cool Semi-Desert Scrub and Grassland (13.0%).

The best represented vegetation formations in the protected area system are Mangrove (89.6% of all Mangrove is in GAP 1 and 2), Temperate and Boreal Alpine Tundra (70%), Tropical Dry Forest and Woodland (43.2%), Benthic Vascular Saltwater Vegetation (42.1%), and Temperate to Polar Scrub and Herb Coastal Vegetation (41.2%), but together these vegetation types make up less than 5% of the protected area system. On average, 25% (median = 17.9%) of the current extent of each formation is represented in the protected area system (Table 3). If all IRAs were added to the protected area system, the average representation of formations would increase to 27%. Formations with the greatest absolute increase in representation when including IRAs in the protected network are Temperate and Boreal Alpine Tundra (19.2%), Cool Temperate Forest and Woodland (5.8%), and Temperate and Boreal Cliff, Scree and Other Rock Vegetation (5.4%). Formations with the greatest percentage increase in representation when including IRAs in the protected network include Temperate Grassland and Shrubland (57.4%), Cool Temperate Forest and Woodland (52.2%), and Mediterranean Scrub and Grassland (35.5%) (Table 3).

3.4 | IRAs and ecosystem services

There are 17,598 HUC-12 watersheds that intersect National Forest System lands, of which 10,292, or 58%, have some fraction (>0%) of their area within a drinking water protection area, supplying water for over 48 million people. To examine the range of importance of these watersheds to protecting drinking water supply, the percentage of the watershed covered by GAP 1 and 2 lands and/or IRA lands is compared to the percentage of the watershed covered by a DWPA. This provides a rough estimate of overall importance. However, EPA data do not contain specific information on which part of the watershed is a DWPA. It is therefore possible that the area of watersheds protected in GAP 1 and 2 lands and DWPAs do not intersect, especially when the percent area of GAP 1 and 2 and DWPA is low. As the percentage of the watershed covered by both a DWPA and GAP 1 and 2 and/or IRA increases, the likelihood of them intersecting increases. To reduce the probability of non-intersection, we narrowed our analysis to only those protected watersheds with at least 50% of their area covered by GAP 1 and 2 and/or IRAs, and 50% of their area covered by a DWPA.

TABLE 3 Ecosystem representation of protected areas and IRAs, as well as representation levels currently in conservation reserves and their potential levels if all IRAs were added to the protection network

National Vegetation Class—formation and land use class	GAP 1 and 2 area (km^2)	IRA area (km^2)	Combined area (km^2)	Current representation	Potential representation
Barren	1,006	23	1,049	12.2%	12.5%
Benthic vascular saltwater vegetation	83	0	84	42.1%	42.1%
Boreal Flooded and Swamp Forest	6,031	38	6,189	19.5%	19.6%
Boreal Forest and Woodland	5,879	140	6,136	23.2%	23.8%
Cool Semi-Desert Scrub and Grassland	92,245	20,421	114,511	10.5%	12.9%
Cool Temperate Forest and Woodland	209,958	105,443	319,600	11.5%	17.3%
Mangrove	2,319	0	2,366	89.6%	89.6%
Mediterranean scrub and grassland	6,946	2,326	9,410	11.9%	15.8%
Salt marsh	13,500	35	13,805	15.5%	15.5%
Temperate and Boreal Alpine Tundra	19,459	5,324	25,172	70.0%	89.2%
Temperate and Boreal Cliff, Scree and Other Rock Vegetation	3,814	971	4,861	21.1%	26.5%
Temperate and Boreal Freshwater Aquatic Vegetation	0	0	0	4.9%	4.9%
Temperate Flooded and Swamp Forest	30,268	1,005	31,879	10.1%	10.4%
Temperate Grassland and Shrubland	24,447	13,548	38,484	3.0%	4.7%
Temperate to Polar bog and fen	1,507	18	1,555	28.1%	28.4%
Temperate to polar freshwater marsh, wet Meadow and Shrubland	7,969	1,499	9,628	15.5%	18.4%
Temperate to Polar Scrub and Herb Coastal Vegetation	794	33	843	41.2%	42.9%
Tropical dry Forest and Woodland	13	0	14	43.2%	43.2%
Tropical Flooded and Swamp Forest	337	0	344	17.9%	17.9%
Tropical freshwater marsh, wet Meadow and Shrubland	2,404	0	2,453	31.3%	31.3%
Tropical scrub and herb coastal vegetation	12	0	13	35.0%	35.0%
Warm Desert and Semi-Desert Scrub and grassland	69,648	1,382	72,423	15.7%	16.0%
Warm Temperate Forest and Woodland	18,562	5,225	24,158	4.9%	6.3%

Note: Classifications are from the National Vegetation Classification—formation or land use class.

Figure 4 displays a range of values for the intersection of protected lands, protected lands with the addition of IRAs, and DWPAs. At its broadest, 489 watersheds are at least 50% covered by a drinking water protection area and at least 50% covered by GAP 1 and 2 lands. If all IRAs were added to the protected area network, the number of watersheds within this class would increase to 780, extending protection to 291 watersheds. At the highest level of protection, there are 145 watersheds that are at least 90% covered by a DWPA and at least 90% covered by GAP 1 and 2 lands. If all IRAs were added to conservation reserves, the number of

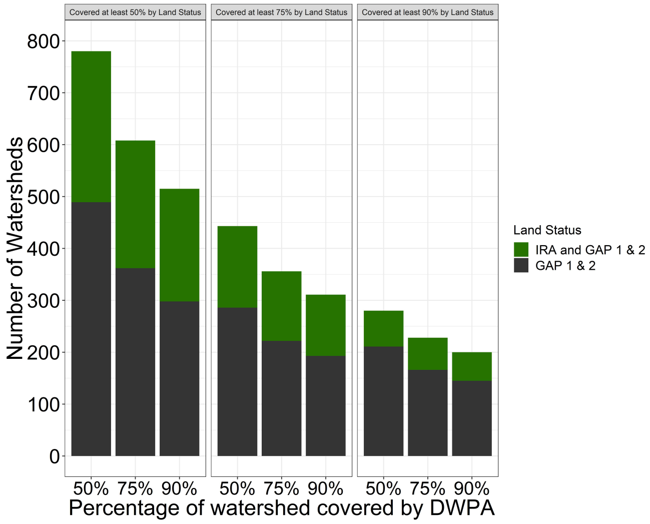

FIGURE 4 HUC-12 watersheds with varying degrees of Inventoried Roadless Area and/or GAP 1 and 2 protection and drinking water protection areas (DWPA).The three panels represent watersheds that are at least 50% (left), 75% (middle), or 90% (right) covered by IRAs and/or GAP 1 and 2 lands, and each bar represents a varying degree of drinking water protection cover (e.g., first bar represents watersheds that are at least 50% in a DWPA)

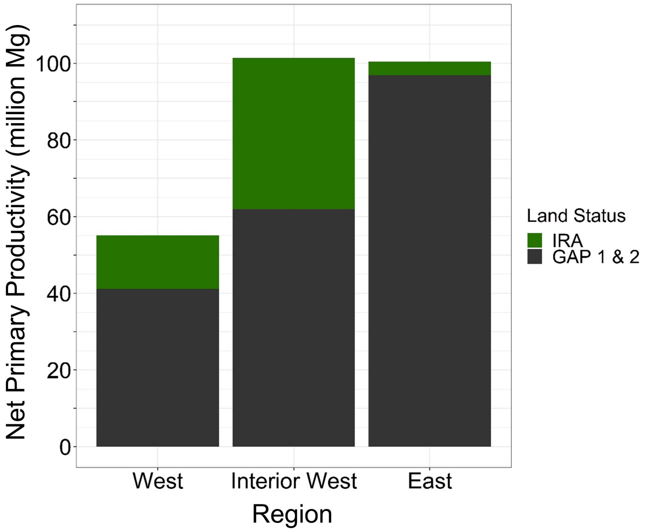

FIGURE 5 Total carbon captured (estimated using net primary productivity) in protected areas (GAP 1 and 2 lands) as well as within Inventoried Roadless Areas in three regions of the contiguous US. Only Gap 1 and 2 lands and IRAs larger than 1 km^2 were included in this analysis

watersheds within this high level of protection would increase to 200, extending protection to 55 additional watersheds.

Across the contiguous US, the existing protected area system captures 199,978,833 megagrams of carbon per year, and IRAs add 29% more total NPP to that captured by the existing system. Within the West, Interior West, and East regions, IRAs contribute 34.0, 63.6, and 3.7% additional NPP to the existing protected areas, despite increasing the area protected by only 19.2, 46.9, and 3.1%, respectively (Figure 5, Supplemental S3). In the West, IRAs capture 13,989,603 megagrams of carbon per year, 39,404,180 megagrams in the Interior West, and 3,607,583 megagrams in the East (Supplemental S3). It is important to note that NPP does not represent carbon sequestration; it represents only the rate at which carbon is fixed by plants (photosynthesis minus live plant respiration) and does not account for losses from decomposition, fire, and so forth. (Lovett, Cole, & Pace, 2006).

4 | DISCUSSION

Our results suggest that IRAs serve important roles in land conservation within the contiguous United States. IRAs maintain some of the wildest places in the country and within states where they occur. IRAs also reduce the isolation of—and provide buffers for—national parks, wilderness areas, and other existing protected lands. Furthermore, some IRAs contain important watersheds for drinking water throughout the US and capture significant amounts of carbon each year relative to existing protected areas. Together, our findings suggest that IRAs are key components of the U.S. system of conservation lands.

Protecting wild lands has been essential to conservation since its inception, and recent research confirms its effectiveness (DiMarco, Ferrier, Harwood, Hoskins, & Watson, 2019). Wild places have more intact ecological processes with fewer local extinctions (DiMarco et al., 2019; Watson et al., 2018). Wild protected areas are therefore more likely to be able to sustain their biodiversity into the future (Aplet & McKinley, 2017; Belote et al., 2017). At the same time, wildlands around the world are disappearing at an alarming rate (Watson, Darling, et al., 2016). Theobald et al. (2019) report that between 2001 and 2017, the U.S. lost almost one hectare of natural area every minute. Our results show that IRAs house some of the wildest places in the U.S. as well as some of the last wild places in states that have been mostly developed (Figure 1; Supplemental S2). These results compare well with Aplet et al. (2005), who used a different metric of wildness to find that the vast majority of the wildest land in the U.S. occurs on federal land in the West and that on the national forests, almost as much of the wildest land occurs in IRAs as in wilderness.

In addition to urging protection of the wildest places, conservation scientists continue to call for increasing the size of protected areas and protected area networks

(Belote et al., 2017; Cantú-Salazar & Gaston, 2010; Gaston et al., 2008). For instance, the Aichi Targets of the Convention on Biological Diversity recommends increasing the proportion of land protected to 17% (CBD, 2014), and recent calls have been made to increase protected areas to cover as much as 50% of land (Pimm, Jenkins, & Li, 2018). It is generally agreed that larger protected areas can contain more species (Cantú-Salazar & Gaston, 2010; Gaston et al., 2008) and more intact ecological processes (Cantú-Salazar & Gaston, 2010), and existing protected areas may be too small to adequately achieve their intended purpose (Hansen et al., 2011). Many conservation scientists have recommended that core protected areas include a "buffer" of adjacent lands that can increase the effective size of reserves (Belote & Wilson, 2020; Hansen et al., 2014; Martino, 2001; Shafer, 1999; Wade & Theobald, 2010). We found that many large protected areas are bordered by IRAs, and these IRAs add to the overall area protected from intensive commercial development and other human land use pressures. With nearly 60% of all IRA area sharing a border with protected areas, and more than 90% of all IRA area within 10-km of one, IRAs increase the effective area of these protected lands. In fact, we have shown that 74% of all IRA land in the lower 48 is connected to a protected area via a close (< 100 m) complex of conservation units composed of IRAs and protected areas (Figure 3). If this distance were extended to 10 km, 98% of all IRA area in the lower 48 would be included in protected area-IRA complexes, increasing the size of the protected network by nearly 159,000 km^2 (a 26% increase in area). The function of stepping-stones will depend on the condition of interstitial lands between IRAs. In some cases, restoration of degraded lands may be required to provide opportunities for establishing large functional protected areas and roadless complexes.

IRAs enhance the size of core protected areas and buffer them from anticipated development (see Hansen et al., 2014; Martinuzzi et al., 2015). For instance, the protected core centered on Yellowstone National Park increases by 29% when considering the surrounding 6,878 km^2 of IRAs. The Greater Yellowstone Ecosystem is expected to experience increased human pressures from residential development, recreation, and land use (Hansen & Phillips, 2018). Other protected areas that are surrounded by IRAs may benefit as well based on the relative increase in effective size. For example, the Great Gulf Wilderness in New Hampshire is only surrounded by 60 km^2 of IRA land, but this represents a nearly 265% increase in the size of this protected area. In Montana, a 5 km^2 segment of the Blackfoot-Clearwater Wildlife Management Area shares a border with a 3,346 km^2 IRA on the southern end of the Bob Marshall Wilderness Complex. The connection among core protected areas and IRAs likely provides for continuous unfragmented ecological processes across these units. The role IRAs play in buffering protected areas from development may be even more critical in the future as developed areas continue to expand (Sohl et al., 2014).

In addition to size, the connectedness of protected areas has been identified as a critical consideration for sustaining biodiversity (Belote et al., 2016; Saura et al., 2018). Protected areas—if not intentionally connected—could become isolated, resulting in loss of genetic diversity of populations and ultimately loss of species (Gaston et al., 2008; Rayfield, Fortin, & Fall, 2011). In some cases, stepping-stones between protected areas can help connect large protected areas (Belote et al., 2016; Hannah et al., 2014). Stepping-stones function by reducing the distance between protected areas and providing temporary refuge for organisms moving across the "matrix" between core protected areas. Belote et al. (2016) showed that IRAs may serve as important stepping stones between Yellowstone National Park and the Bob Marshall Wilderness-Glacier National Park protected areas (see Supplemental Figure S5 in Belote et al., 2016). While land between IRAs and protected areas may include roads and be susceptible to human development, recognizing the value of IRAs as part of complexes of core protected areas should be an important consideration of conservation planners working to maintain large blocks of intact and wild lands and enhance the size of the national system of protected areas.

While IRAs could serve as buffers around protected areas, reduce their isolation, and increase their connectivity, adding them to the system would not dramatically increase the representation of ecosystem types (i.e., vegetation formations). Of the 23 formations currently in the protected area system, 10 are already above the 17% Aichi threshold set by the Convention on Biological Diversity in 2010 (CBD, 2014), and only two (Cool Temperate Forest and Woodland and Temperate to Polar Freshwater Marsh, Wet Meadow and Shrubland) would move above 17% if IRAs were included in the protected area system. IRAs would not contribute any new formations to the system. Using a classification system consisting of 83 ecoregions, DeVelice and Martin (2001) found a similarly modest increase in the number of ecoregions achieving a 12% threshold (the informal scientific standard before 2010) if roadless areas were added to the nationwide protected area system. In studies conducted at a regional scale, Strittholt and DellaSala (2001) found that roadless areas in the Klamath-Siskiyou ecoregion added 96 new types to the 42 (out of a possible 214) types already protected above a 25% threshold, and Crist, Wilmer, and Aplet (2005) found that protecting the roadless areas of the northern Rocky Mountain states would add six vegetation types to the 12 (out of 29) that exceeded a 12% threshold and add a new type, Bur oak woodland, to the protected area system. All three of these studies found IRAs to occupy generally lower elevations than the existing protected area system, accounting for the increase in representation. In contrast, we found IRAs to occur at higher average elevation (Supplemental S3), likely because our analysis included all GAP 1 and 2 lands, not just those on national forests.

In order to better understand the value of national forest IRAs, we also examined the role IRAs play in delivering ecosystem services, a critical rationale for conserving natural areas (Balmford et al., 2002). Watershed delivery of drinking water (Keeler et al., 2012) is among the most critical ecosystem services for mitigating climate change and providing for human well-being (Costanza et al., 1997). Road-building and roads can impair watershed condition (Potyondy & Geier, 2011), and IRAs may play a key role in protecting watersheds important for delivering drinking water (DellaSala, Karr, & Olson, 2011). IRAs add significantly to protection of watersheds important for delivering drinking water to people, increasing the number of watersheds dominated by DWPAs that are also dominated by protected areas by as much as 60%. Our intention in this analysis was to quantify the contribution of IRAs to watershed protection, as these values were highlighted in the 2001 Roadless Rule. The Forest Service's analysis of the Rule acknowledged that “[r]oads have long been recognized as the primary human-caused source of soil and water disturbances in forested environments” (USDA Forest Service, 2000, pp. 3–44). Roads cause multiple negative impacts on water quality and hydrology (Gucinski, Furniss, Ziemer, & Brookes, 2001) and can continue to disrupt hydrology for years, even after closure (Sosa-Pérez & MacDonald, 2017). By restricting road building in IRAs, the Roadless Rule helps protect water quality for watersheds upon which people depend (DellaSala et al., 2011).

In addition to water delivery, the ability of ecosystems to capture atmospheric carbon through photosynthesis and vegetation productivity is increasingly recognized as a critical ecosystem service (Dinerstein et al., 2019). The carbon captured and stored by ecosystems is a key service that mitigates the would-be impacts of human-induced climate change (Naidoo et al., 2008), and protecting carbon-capturing ecosystems from development has emerged as a key conservation strategy to aid climate change mitigation (Dinerstein et al., 2019). Our results show that IRAs add disproportionately, relative to the area added, to the carbon captured by existing protected areas. Of course, the type of management and strategies for best maintaining an ecosystem's ability to capture and store carbon will vary by disturbance history and context (Kashian, Romme, Tinker, Turner, & Ryan, 2006; Law et al., 2018). Further work is needed to understand the co-benefits and tradeoffs between carbon storage and management aimed at addressing fire mitigation or timber harvest (Buotte, Law, Ripple, & Berner, 2020; Johnston & Radeloff, 2019; Onaindia, Fernández de Manuel, Madariaga, & Rodríguez-Loinaz, 2013).

IRAs may be good candidates to consider as “other effective area-based conservation measures” (OECMs) when assessing national and international conservation targets. Our work responds to calls to identify and assess OECM conservation value (IUCN-WCPA, 2019). However, while the Roadless Rule currently affords protections from road building and commercial timber harvests, IRAs remain vulnerable to conservation demotion unless protected by law.

We note that while our assessment did not include Alaska due to lack of some data sets we used in the contiguous US (e.g., human modification, our index of wildness), IRAs located on the Tongass National Forest may be similarly valuable and yet threatened by removal of the protections afforded by the Roadless Rule. Before such changes are made to demote IRAs' status on the Tongass or other national forests, an assessment of their conservation value should be conducted to more fully understand the roles IRAs play in maintaining ecological values.

5 | CONCLUSIONS

Even as conservation scientists call for additional area to be conserved, other researchers have identified the potential threat posed by downgrading, downsizing, and degazettement of protected areas (Golden Kroner et al., 2019). IRAs are currently administered under the Roadless Rule and are not formally protected by legislation. Since 2001, many wilderness areas have been designated from existing IRAs. In fact, 74% of all wilderness areas designated on US Forest Service land since 2000 were first IRAs. However, lacking legislative protection, IRAs may also be candidates for downgrading by the U.S. Congress or administrative rule changes. Such downgrading could open these important conservation lands to commercial resource extraction, road building, or other damaging activities. Given their conservation potential and uncertain status, it is critical that their values be assessed before any decision is made about downgrading. Because of their special qualities, maintaining roadless areas has been a goal of conservation for at least 80 years (Marshall & Dobbins, 1936), and our results reveal their continuing conservation value. Through their effect on protected area quality, size, and connectivity, and their influence on valued ecosystem services, national forest IRAs make a valuable addition to the nation's protected area system.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Gregory H. Aplet and R. Travis Belote conceived of the study. McKinley J. Talty and Kelly Mott Lacroix conducted analyses. McKinley J. Talty, Kelly Mott Lacroix, Gregory H. Aplet, and R. Travis Belote wrote the paper.

DATA AVAILABILITY STATEMENT

All data are publicly available.

ETHICS STATEMENT

No ethics approval was required for this research.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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