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ANALYSIS

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Ecosystem services benefits from the restoration of non-producing US oil and gas lands

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Fossil fuel infrastructure has important land-use impacts within the United States, including the environmental consequences of affected land that persists beyond the lifespan of wells. Here, we estimate the ecoregion-specific fifty-year present-value net benefits of restoring lands that are associated with non-producing wells in the conterminous United States on the basis of select ecosystem services—agricultural sales and carbon sequestration. We identify more than 430,000 restorable wells that occupy more than 800,000 ha of land. The present value of ecosystem services benefits was US$21 billion (2018) while the restoration costs were US$7 billion. Deciduous forests, grasslands and Mediterranean ecoregions had large net benefits, whereas arid and semi-arid regions were often negative. Focusing on select ecoregions of the United States would provide higher returns on investment in the form of environmental and economic benefits. Although our results suggest an ecoregional hierarchy, the restoration of all abandoned fossil fuel lands will have benefits at the local, regional and national scales, including food security, protection of biodiversity and restoration-related job opportunities.

Energy infrastructure is presently the greatest driver of land-use change in the United States[1–3]. Although emerging energy resources, such as wind and solar, are growing rapidly, fossil fuel production continues and is predicted to expand into the foreseeable future[4,5]. With the stagnation of conventional fossil fuel production, unconventional techniques (for example, horizontal drilling combined with hydraulic fracturing, commonly known as fracking) have enabled production to increase in the United States[6]. The nature of onshore fossil fuel development involves conversion, modification and fragmentation of landscapes[7,8]. Lands are completely converted when fossil fuel infrastructure (such as well pads) removes all biological material and the associated ecosystem services (ES)[3,9]. Modification includes the conversion of habitat from the location-specific naturally occurring biological community to a degraded state (for example, pipeline rights-of-way through forest). Fragmentation is the reduction in size of contiguous natural habitat and isolation of remaining habitat blocks and may have a greater impact than the infrastructure footprint alone[2] (Fig. 1). These changes have numerous environmental and socioeconomic impacts[10,11], representing important negative externalities that current markets typically fail to address[12].

Oil and gas well production is sensitive to diminishing marginal productivity, eventually reaching zero[13], which causes the economic benefits to be temporary, whereas the environmental costs continue beyond the lifetime of wells[14]. Non-producing fossil fuel infrastructure has long-lasting impacts on society, including pollution and the associated negative health impacts[15], negative ES effects[1,3], decreases in property value[16] and agriculture losses[1,17]. The foregone economic and environmental opportunities that this land could provide are also of importance; one might see this problem as a rural example of the widely studied 'urban brownfield' phenomenon[18] (Fig. 1e). The restoration of lands with non-producing well infrastructure can therefore provide long-term economic and environmental benefits to society[19]. Here we use the term restoration to mean "the process of assisting the recovery of an ecosystem that has been damaged, degraded or destroyed" as it is defined by the Society for Ecological Restoration[20].

Many federal and state agencies have best-practice guidelines or requirements for the restoration of non-producing well infrastructure lands[21]. However, rules, enforcement and/or funding are often inadequate to encourage restoration, such that many well sites remain after their productive lives[22]. These 'legacy' wells can create a variety of hazards beyond their landscape effects, such as gas migration and fugitive emissions[15,22–25]. The costs of restoration, limits of its effectiveness and funding sources are also poorly understood. There are few peer-reviewed published reports on the land restoration costs for oil and gas well lands[26] but, by many accounts, the fees collected from fossil fuel producers are inadequate to meet all restoration needs, especially when expensive well-plugging requirements are met first[19,27].

Quantifying restoration potential

There is little information on how many non-producing but restorable well sites exist in the United States and their associated landscape impacts. Allred et al.[1] showed that there is a high level of agricultural and greenhouse gas impacts from landscape changes caused by the fossil fuel industry. However, assuming that a large number of non-producing wells exists across the landscape, there are potential benefits to recovering some of these losses in the form of renewed ES. Combined with estimated investment costs of restoration, a benefit–cost analysis would illustrate the economic incentives of large-scale restoration. With the predicted rise in unconventional well sites over the next several decades and continued retirement of old conventional wells[19], the value of this process would provide society with vital information regarding the re-establishment of lost values described in previous literature[1,3].

Here we estimated the land area occupied by restoration-eligible non-producing well sites in each Level II ecoregion[28] within the

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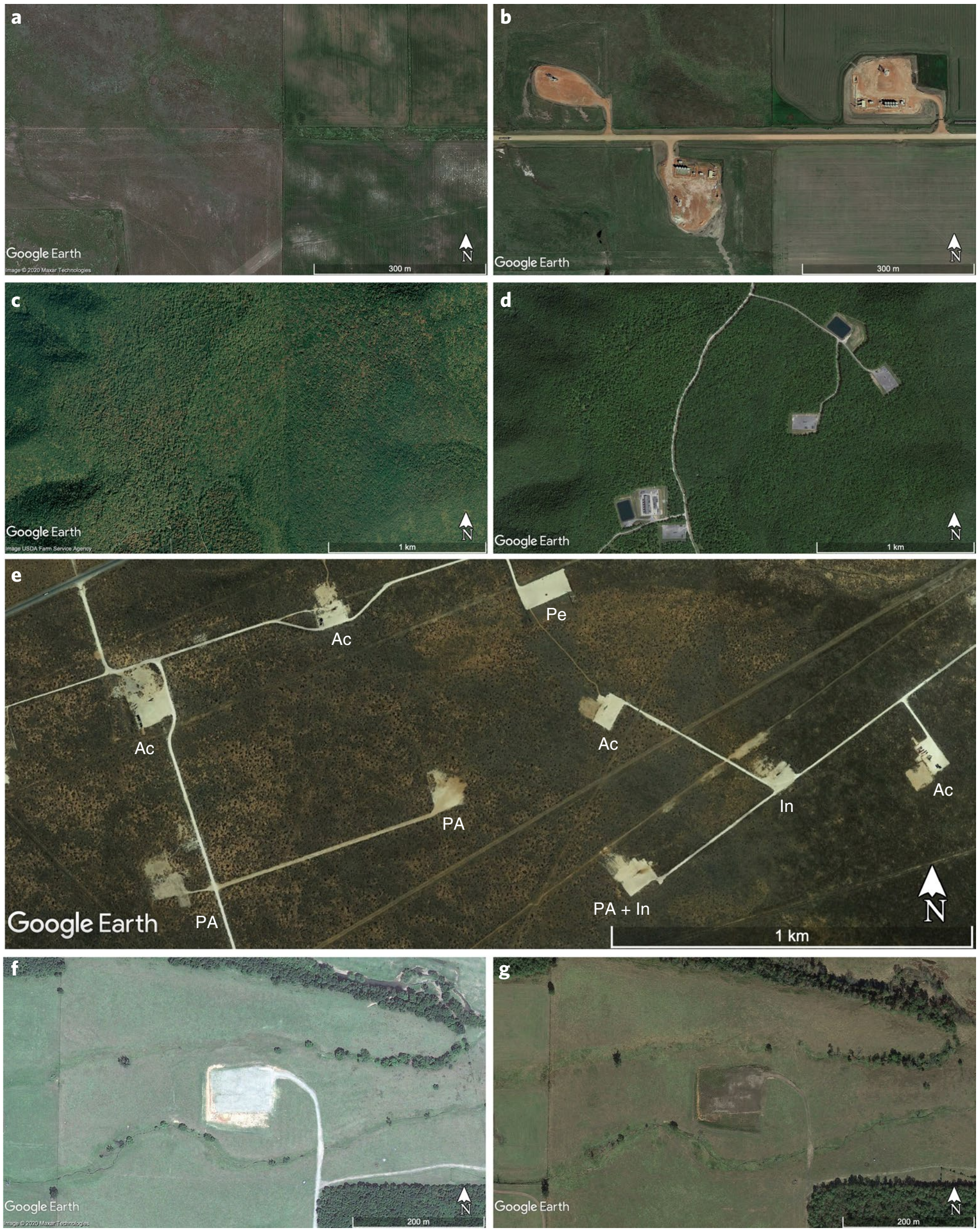


Fig. 1 | The effects of oil and gas development on landscapes across the United States. a, Temperate grasslands and cropland before development; 2010, North Dakota. **b**, Temperate grasslands and cropland after development, with well pads and associated infrastructure visible; 2016, North Dakota. **c**, Temperate forest before development; 2010, Pennsylvania. **d**, Temperate forest after development, with well pads and associated infrastructure visible; 2018, Pennsylvania. **e**, Oil and gas associated infrastructure eligible for restoration in the Chihuahuan Desert, 2020, Texas. **f**, Ranch land developed; 2009, Arkansas. **g**, Ranch land undergoing restoration; 2014, Arkansas. PA, plugged and abandoned well site; In, inactive well site; Ac, active (producing) well site; Pe, permitted well site (that is, undergoing drilling operations).

conterminous United States. We estimated the present restoration costs along with ES benefits of carbon sequestration and agricultural sales, discounted over 50 years. In our case, restoration includes the active removal of oil and gas infrastructure, site preparation and initial ecoregion-specific vegetation planting followed by natural regeneration of the site over time to match the surrounding landscape. We also provided a sensitivity analysis of uncertainty for our estimates and a coarser estimate of total ES to be potentially recovered. Our goal was to determine the benefit–cost ratio and total benefits of well restoration on the basis of these two key ES and to identify the geographical areas of the conterminous United States that, if re-established, would generate the greatest economic and environmental benefit relative to cost. This analysis could facilitate interest in a large-scale land restoration process across the country and be a global model for oil and gas land restoration.

Land and ES impacts

We found more than 400,000 restoration-eligible wells, corresponding to a total area of over 800,000 ha (Table 1). Temperate deciduous forest, grassland and pasture, as well as row crops made up the vast majority of the landscapes available for restoration. Many of these eligible lands have been non-producing for long periods of time. For conventional wells, the median year of abandonment was 1993, whereas the median year of abandonment for unconventional wells

Table 1 | Summary of the area and number of wells available for restoration for different types of habitat

Variable	Deciduous forest	Coniferous forest	Grasslands/pasture	Arid/semi-arid lands	Crops	Mediterranean	Total
Restorable area (ha)	250,570	6,462	360,642	94,815	138,583	32,058	852,635
Restorable wells	128,681	3,231	183,887	47,782	70,739	19,857	434,320

Table 2 | The benefits and costs of carbon and agriculture (US$, 2018) over a fifty-year period on oil and gas infrastructure lands eligible for restoration

Variable	Value
Total carbon sequestration (tonnes, 2018–2068)	144,104,677
Total carbon sequestration value (US$, 2018–2068)	7,307,516,675
Total agricultural value (US$, 2018–2068)	14,862,093,036
Methane production cost (US$, 2018–2068)	846,574,570
Total restored value (US$, 2018)	21,323,035,141
Cost of restoration (US$, 2018)	6,917,839,227
Payback value (benefit/cost)	3.08

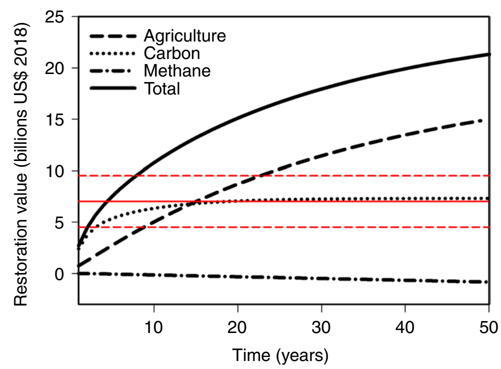


Fig. 2 | The benefits and costs of oil and gas lands eligible for restoration over a fifty-year time period. The solid and dashed horizontal red lines show the mean estimated restoration costs ±1 s.d., respectively. Total benefits = carbon + agriculture − methane. The breakeven time occurs during year 5 ± 3 years.

was 2011 (Supplementary Fig. 1). The later date for unconventional wells is indicative of more-recent increases in unconventional drilling activity.

The total present value of carbon sequestration and agricultural benefits from the restoration of eligible oil and gas well infrastructure lands over 50 years is estimated to be US$21.3 billion (2018), while the cost of restoration is estimated to be about US$6.9 billion (2018), yielding a benefit–cost ratio above 3:1 (Table 2). Using a Chapman–Richards function to model ecosystem recovery after restoration, we found that the break-even point occurs during year five (Fig. 2). Agriculture makes up about two-thirds of the value, whereas climate regulation related to carbon storage comprises the balance. Estimated methane production by increasing cattle numbers on new agricultural lands causes a reduction in benefits by about 5%.

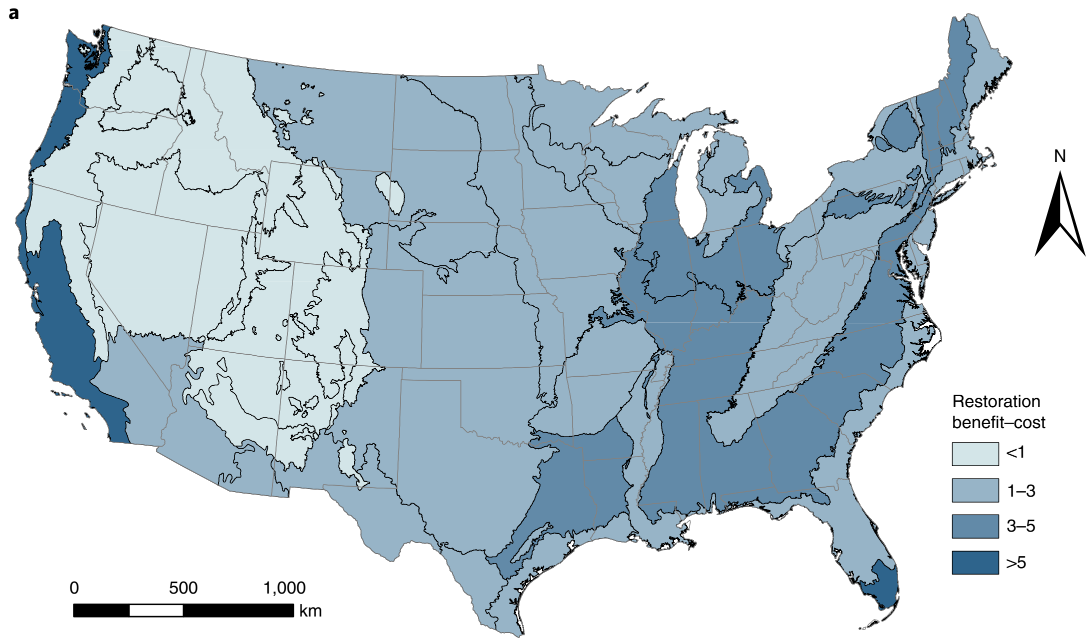
The net benefits varied by ecoregion, with a few regions showing negative net benefit (that is, higher costs compared with the benefits) while most areas showed benefits substantially higher than the costs (Fig. 3a and Supplementary Table 1). The overall benefits, which were sensitive to both the relative value of land and the total number of restorable well sites, also varied widely between ecoregions (Fig. 3b and Supplementary Table 1). In general, grasslands and deciduous forest regions had large benefits, both relative to costs and in total magnitude, whereas arid/semi-arid regions had low values for both. The Mediterranean climate of California had the largest benefit–cost ratio and a high total value owing to the high-economic-value farmland in the region[29].

Uncertainty effects

To further explore our benefit–cost results, we modelled variation in several of our input variables. This sensitivity analysis indicated that our results were responsive to some variables that are highly uncertain, but robust to other variables (Supplementary Fig. 2). Mean national agricultural production had low variation from 2008–2016, and the 2017 county-level estimates that we used deviated by only 2% from the ten-year mean, so we suggest that our agricultural estimates have high certainty (Supplementary Fig. 2a). Although year-to-year county-level variation may be high, it seems that gains and losses at the local level are balanced at the national level. Restoration costs were uncertain due to the paucity of research and available information on this process, but within 1 s.d. of our estimate; the break-even point and total benefits were qualitatively similar, varying by about ±2 years (Fig. 2 and Supplementary Fig. 2a). The societal value of carbon sequestration is particularly uncertain and depends on the choice of discount rate[30]. This uncertainty is reflected in the substantial variation in our estimated benefits of US$2–21 billion. Note that, even at the lower bound of estimated benefits (agriculture and carbon combined) and highest estimated costs of restoration, there was a positive benefit–cost ratio (about 1.6:1; Supplementary Fig. 2a,b). Analysis of the present value of net benefits per well confirmed that, even at the individual level, social costs of carbon are responsible for the largest uncertainty in our estimated values (Supplementary Table 2). If biome-specific comprehensive ES (that is, including estimates of all ES) were used, total benefits would rise to almost US$50 billion (2018), about a 7:1 benefit–cost ratio (Supplementary Fig. 2c). Including comprehensive ES would incorporate many other positive restoration variables, such as soil retention, water filtration and aesthetic value, benefits that are beyond our two select services. However, it should be noted that these coarse variable measurements fail to address local variation in ES. Measuring the sensitivity of these ES benefits using coefficients of sensitivity that are conventional in the literature[31] was not possible in this circumstance because they are dependent on percentage growth in ES, which is unattainable when working from an initial condition with zero ES value. Regional economic multiplier effects of additional agricultural production increased total economic benefits to a similar degree (Supplementary Fig. 2d). Considering that agricultural sales seem to have less uncertainty and are the larger contributor to ES benefits, we argue that the overall net benefits nationally are plausibly positive under all of the scenarios described.

Positive economic and environmental returns

Our results show that restoring non-producing oil and gas associated lands has a positive economic impact for most ecoregions over a relatively short period of time. The agricultural potential of sites



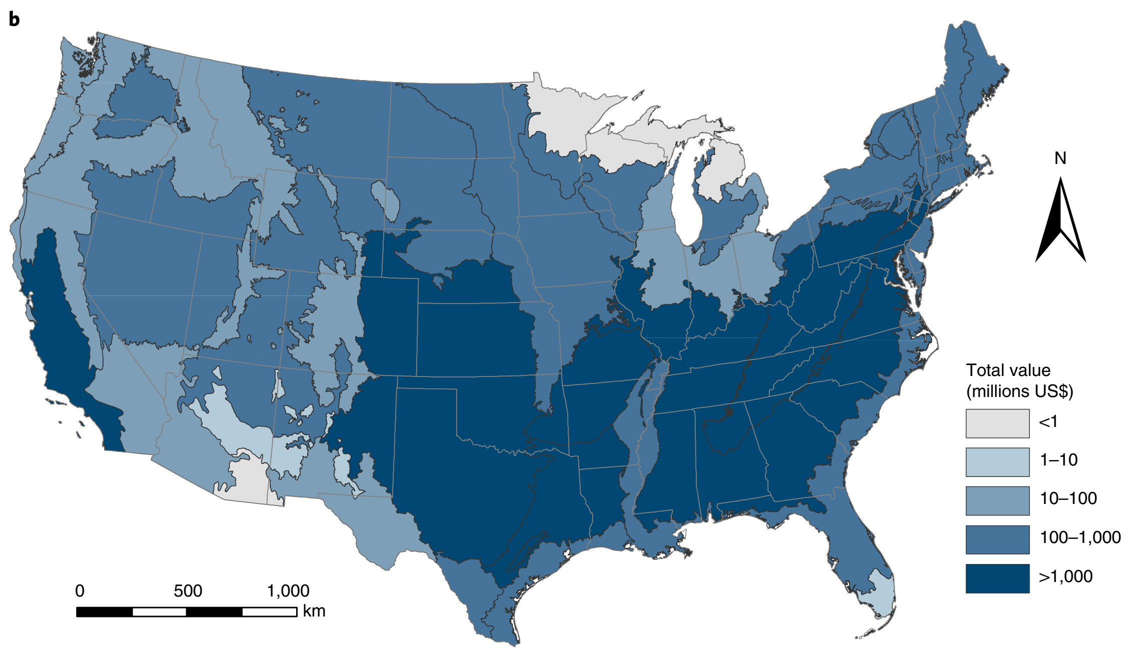


Fig. 3 | Map of restoration values in EPA Level II ecoregions. a,**b**, Map of EPA Level II ecoregion[28] values for the benefit–cost ratio (**a**) and the total benefits (US$, 2018) (**b**) of restoring lands that are associated with restoration-eligible well sites.

is responsible for about two-thirds of the value. This agricultural economic impact could also contribute to economic multiplier effects, improving economic activity in many rural communities. Land development from oil and gas activity is pervasive but scattered over a large area[3,32], making it potentially less obvious to the casual observer. Most individual farms are probably not impacted to a great degree but, in aggregate, the total impact on the agricultural economy is large. The oil and gas industry typically follows a boom-and-bust cycle[33] so, although the benefits of the economic industry can be short-lived, the lasting negative impacts on land use and ecosystem function in agricultural systems (for example, soil erosion, invasive species spread) can remain.

The beneficial effects of increased carbon storage comprised one-third of the total value, but represented only 2.4% of one year's worth of US carbon equivalent emissions[34], showing that restoration at this scale will have little effect on long-term emission trends. However, restoration efforts of this size combined with efforts at improved agricultural practices on these lands could have further benefits[8]. If some of the lands available for restoration that are now classified as agricultural lands were instead converted to forest (where the natural vegetative cover is forest[35]), the carbon impacts would be higher. Planting trees is estimated to have a major impact on climate change if carried out across parts of the world conducive to forest growth[36].

Discussion

The estimates that we provided can be used to produce recommendations for societal action. Since the turn of the 21st century, technological advances in unconventional oil and gas production, along with increased efficiency and decreased costs for wind and solar energy, have led to a surge in US energy sector development. The increases in energy production now threaten many landscapes, some of which had seen little industrial activity and were relatively intact and unfragmented[9,37]. Land development and modification is a major source of environmental degradation across the United States, and energy-related development is predicted to be the largest driver of short-term changes in land use[2]. One way to mitigate this predicted change is to restore lands that were previously used for energy production that are now non-producing. It is striking to consider that greater than 8,000 km^2 of US land is presently occupied by non-producing oil and gas infrastructure and therefore has negative economic, environmental or aesthetic value. These lands are probably exerting costs on society beyond what we have calculated, including lost adjacent property values and negative health and welfare impacts[38–41]. As some of these lands have been in this non-producing but unrestored state for decades (Supplementary Fig. 1), the cumulative ES costs have been extensive.

The negative effects of non-producing infrastructure on the economy and the environment are negative externalities that one could argue are best remedied by fees on the fossil fuel industry. Indeed, state or federal governments impose fees on oil and gas development, typically as well bonds. However, these fees, which vary by state and ownership (public versus private lands), almost never meet the full costs, including plugging the well, removing infrastructure and restoring the landscape back to its original condition[19,27]. Thus, raising well bonds to a level that adequately supports full restoration is strongly warranted. Public spending (either state or federal) could also be used and, as the benefits are both local (for example, agricultural sales) and national and/or global (for example, carbon storage), public financing of restoration could be defensible. Regardless of funding sources, our study shows that the restoration of lands containing non-producing oil and gas infrastructure is economically efficient. Furthermore, opportunities for this investment will increase as older wells become exhausted and new wells that are destined for future abandonment are drilled.

Land development, modification and degradation are important environmental and economic factors across the world. There are many examples, including urban brownfields[18], overgrazing[42], poor farming practices[43], unsustainable resource extraction[44] and—in this study—non-producing oil and gas infrastructure. The restoration of these types of land provides numerous benefits. Most notably, oil and gas lands that are no longer productive offer no economic benefits, yet their negative environmental and social effects continue indefinitely unless restored. Investment in restoration could help to partly mitigate this negative socioeconomic impact locally while also providing benefits that extend to the world[45,46].

Methods

We first divided the conterminous United States into EPA Level II ecoregions[28] to analyse as separate well-impact units. Each ecoregion has distinctive climate and vegetation characteristics, so we assumed ES valuations would be relatively similar within each ecoregion, accounting for the spatial distribution of wells.

Estimating restoration-eligible wells and landcover type. For each ecoregion, we imported the respective shapefiles into the Enverus[47] browser database, which contains information on all of the US oil and gas wells. Within each ecoregion, we searched for all of the wells that were classified as 'plugged and abandoned', 'abandoned', 'inactive', or 'temporarily abandoned', and determined them to be 'non-producing.' We assumed that all of these non-producing well categories would not have future production. Wells classified as 'temporarily abandoned' often remain non-producing for many years[48] and sometimes this status is used to avoid restoration obligations[49]. We cross-checked each selected well with oil and/or gas production records[47] to confirm that oil and/or gas production had ceased. Although errors in record keeping may misclassify or provide poor location records on some wells, the Enverus database is the most complete one available. The term 'orphaned' is used by the oil and gas industry to refer to wells in some form of abandonment, but Enverus only occasionally classifies wells as orphaned, so we ignored this category.

For each Level II ecoregion, we randomly selected 100 conventional and unconventional wells for detailed analysis (or all wells of each category if less than 100 were present for that category). Although it would be desirable to sample every well, the large number of non-producing wells ($n = 1.4$ million) made population measurements impractical. Machine learning could be used to analyse all of the wells, but intraecoregion topographic variation, seasonality of satellite images, well infrastructure variation and the complex decisions that determine well status make this process difficult without a case-by-case visual inspection (Fig. 1). For each randomly selected well, we recorded its location, status and date of last production from Enverus. We next examined the satellite image on Google Earth Pro at the well's location to determine the land status. It was categorized as already restored if there were no visible landscape modifications indicative of well infrastructure (for example, a well pad and roads; Fig. 1g). If the well site had not been restored, there was obvious evidence of well infrastructure (see fig. 3 of ref. [32] for satellite imagery interpretation). To be classified as restoration-eligible, the well had to be non-producing and located on well infrastructure that did not contain other producing wells. Many modern (that is, unconventional) well pads contain multiple wells, so the presence of an abandoned well did not automatically make the land restoration-eligible. Our assumption for this definition was that no future wells would be drilled on infrastructure that was supporting only non-producing wells, although we have no practical way to test this assumption. However, it should be noted that oil and gas fields follow a typical pattern of increased drilling, peak production and decline whereby, during the latter phase, drilling new wells becomes less common and the rate of abandonment increases[50]. The fact that this pattern leads to permanent non-producing status has been seen in many oil and gas fields[48]. From the total number of ecoregion-specific non-producing wells, the proportion of those restoration-eligible from our random samples, and the average footprint of oil and gas wells[2], we were able to estimate the amount of land within each ecoregion that was restoration-eligible. Although some have suggested that unconventional wells have decreasing land impacts as more wells are drilled[51], published research indicates that the relationship between well counts and land-use impacts is linear[3,32]. Multiple unconventional wells can be drilled on single well pads, perhaps leading to reduced land impacts per well as more wells are drilled, but we suggest the linear relationship measured in published studies is due to increasing needs for supporting infrastructure (for example, pumping stations) as oil and gas production increases.

To determine pre-well land cover, we examined the immediate land cover surrounding each well and assumed that this cover was the previous condition of the landscape before drilling. If well infrastructure was on a boundary between two different types of land cover (for example, located on a row crop/grassland margin), we assigned the land cover that composed the majority of the linear edge of the land area impacted. All areas were classified as either 'temperate coniferous forest', 'temperate deciduous forest', 'arid/semi-arid lands', 'temperate grassland', 'Mediterranean' or 'tropical wet forest' (that is, south Florida) similar to EPA Level I ecoregion designations[28]. Three ecoregion types that are dominated by conifers were classified together as 'temperate coniferous forest' and two southwestern arid environments (southeastern semi-arid highlands, temperate sierras) were classified together with other arid and semi-arid lands. The lumping of Level II ecoregions into Level I designations (equivalent to biomes) was not ideal, but was necessary for estimating parameters for ecosystem recovery (see the next section). As the arid and semi-arid lands are grouped together but we have ES parameters from only true deserts, we are probably presenting a conservative estimate for carbon storage for these habitats. For agricultural land that was in row crops, we created a separate category (that is, crops) while grazing lands (both natural and human-maintained pastures) were classified as temperate grasslands. The senior author (M.D.M.) cross-checked the first 200 of each researcher's well classifications to confirm that the methods were being followed correctly between individual researchers.

ES valuation. We chose to estimate two major ES in our analysis—agricultural value and carbon sequestration values. We chose these two because they have biome- or location-specific values that are well documented[48,52] and are relatively easy to quantify compared with some other ES (for example, cultural valuations[53]). Most ecoregions have few, if any, published comprehensive ES valuations[3]. However, we also used coarser biome-level comprehensive ES values to estimate the total potential value (see the 'Sensitivity analysis' section below).

Our ES estimate (ESV) in a given time period (t) was given by the sum of the individual ES values. The value of each service was found by the product of the contemporaneous biomass ($L(t)$) and the ES unit value. For the value of carbon sequestration, we use the social cost of carbon (SCC) while the agricultural value is reflected in the market prices (P_{Ag}). Each of these parameters is discussed in detail below.

$$\mathrm{ESV}(t) = \mathrm{SCC} \times L(t) + P_{\mathrm{Ag}} \times L(t)$$

Biomass recovery. Biomass recovery was used as a proxy for land cover recovery over time and was modelled using the Chapman–Richards growth equation[54,55]. Biomass, and the carbon stored in that biomass, is a valid measure of restoration, as biomass should be maximized when the community reaches the dominant prevailing state[56]. We therefore assumed that biomass stored in an ecosystem is indicative of maturity, as this value typically follows logarithmic growth during succession.

$$L(t) = L_{\max}\left(1 - e^{-kt}\right)^r$$

The contemporaneous biomass is a function of the maximum possible level, $L_{\max}$, and k and r represent empirical growth parameters that scale absolute growth and shape the growth function, respectively. These parameters were identified for each biome from the available literature[57,58]. We modelled our recovery time at 50 years, a value that is within the range typically seen for land to return to its predevelopment state[59], but we used different k and r values, representing different rates of recovery estimated for different ecoregions in the literature (Supplementary Table 3). Regardless of the recovery time, we modelled all of the habitats and ES values over a fifty-year period. While the final value for L after 50 years is constrained by $L_{\max}$, the rate of growth is controlled by k and r. As our final annual ES values reach an asymptote, we have less uncertainty of the final annual values compared with the rate at which the habitat recovers to the dominant prevailing state. Our model did not take into account changes in carbon storage due to natural disturbances (for example, fire).

Social cost of carbon. The per-unit value of carbon stored within the ecosystem was represented as the social cost of carbon, the discounted sum of all future damages associated with a one-unit increase in CO_2 emission. The degree to which future value should be discounted is uncertain and can have large impacts on the estimated SCC. Auffhammer[60] offered a thorough examination of the determinants of SCC values, and identified the Interagency Working Group established by the US federal government in 2009 to establish an official SCC value for use in regulatory actions[61]. These values are produced by conducting 50,000 simulations in three different integrated assessment models (for a total of 150,000 simulations) across a variety of modelling assumptions. The working group provided updates for these values through 2017 that we adopted for our analysis. Recent official estimates (since 2017) for SCC are substantially lower due to limiting analysis to domestic impacts of climate change and uniformly higher discount rates, which have received broad criticism[62].

The central estimate from the 2017 update is SCC = \$50.87 (US\$, 2018; 3.0% discount rate). We used this value for our calculations of the restored value of carbon from the Chapman–Richards model, but also provided a sensitivity analysis to model variation in the estimated carbon costs (see below). As unconventional and conventional infrastructure have different sizes of area typically developed[2], we calculated the total restored area value for an ecoregion separately for each well type.

Agricultural value. We estimated the potential agricultural benefits from the restoration of wells for each Level II ecoregion designation using the number of reclaimable wells per county, amount of reclaimable agricultural land per well and county-level data on total agricultural sales per hectare[63]. The agricultural sales in the National Agricultural Statistics Survey (NASS) database[63] include all products, plant and animal, and we assumed that restored wells would return crop and livestock benefits in the same proportion as they exist presently (at the county level). We assumed random well infrastructure placement and that oil and gas companies did not attempt to avoid highly productive agricultural areas. Well placement is presumably based on geology, but if there is some consideration of land impacts[51], our estimates could be an overestimate of sales losses. However, there is little information in the literature about industry decisions on well placement. We assumed all agricultural effects of non-producing energy infrastructure were negative due to lost land productivity, a result that is well documented in the literature[1,10,48,64]. Some farmers and ranchers report benefits from abandoned oil and gas infrastructure, (for example, enhanced access to land[64]), but loss of productivity and failure to reclaim lands is a top concern among many farmers and ranchers[65] and probably creates monetary losses.

The number of restorable wells per county (RW_i), where i indicates county, was estimated using the number of wells per county within each ecoregion (NW_i) and the proportion of reclaimable wells per county (PrW_i), calculated by the random selection of wells ($n = 100$ for both conventional and unconventional, if present) in each ecoregion (see above).

$$RW_i = NW_i \times PrW_i$$

To determine the area of reclaimable land per county (RL_i), we used the summed proportion of land-use types (livestock production from grassland/pasture or arid/semi-arid rangeland, and crop production) that can be used in agriculture (P_A) premultiplied by the area developed per well (A_W), as estimated by Trainor et al.[2].

$$RL_i = A_W \times P_A$$

Finally, we used the National Agricultural Statistics Survey[63] to find county-level agricultural sales (VA_i). We focussed on agricultural sales rather than net revenues or profit because our analysis focused on assessing the benefits of the ES themselves. Even in the presence of additional costs to agricultural production, there is still value from the provisioning service alone. We drew on the fact that markets reveal the preferences of economic agents that inform their willingness to pay for goods and services. These market prices are affected by input costs, but still represent an effective per-unit value that the agricultural production provides to society[66]. Summing across all relevant counties, we calculated the total value of agricultural production for each ecoregion.

$$TV = \sum_{i=1}^{n} RW_i \times RL_i \times VA_i$$

As in the carbon estimates, we calculated conventional and unconventional well sites separately and then summed these values to get a total potential annual value for agricultural lands for each ecoregion.

As we expect that restored grassland/pasture could support new ruminant animals, we adjusted these carbon estimates to account for the additional methane that could be produced by cattle (NC) added to the landscape after restoration. While other ruminants also produce methane in the United States, cattle make up 91.9% of individuals[63]. Using per-individual production levels of methane[67,68] to calculate methane production by these types of livestock, cattle make up the vast majority (98.9%) of all US livestock methane emissions. For each ecoregion, we calculated the number of cattle per hectare by taking the number of cattle produced per county (C_i) and dividing it by the number of hectares devoted to agricultural area (A_i)[63]. This value was multiplied by RL_i (see above) to get the number of cattle per county that could be added after restoration. These values were summed to estimate the total number of new cattle per ecoregion that could be added after restoration.

$$NC = \sum_{i=1}^{n} \frac{C_i}{A_i} \times RL_i$$

We estimated the annual cost of methane production from new cattle in CO_2 using the measured methane production (55 kg per individual)[67] and the CO_2 equivalent of methane (21×)[56]. This value was then modelled using the Chapman–Richards equation (but as a negative benefit) as in other carbon value calculations described above. Note that properly grazed ruminants may increase ecosystem carbon storage, so our calculations may overestimate their carbon emissions[43].

We recognize that aspects of agriculture other than ruminant production (for example, type of forage available, run-off impacts on anaerobic bacteria methane production) can influence greenhouse gas emissions that could partially offset carbon storage. Owing to the great variety in carbon emissions between different crops and farming practices, we were not able to include this model variable. As the United States moves toward more renewable energy production, and hopefully more sustainable farming practices, there is an opportunity to get the full value of carbon stored in agricultural lands.

Economic discounting in environmental economics. People tend to assign less value to future events compared with the exact same events in the present moment. Economists address this issue with 'discounting,' which translates a value that will be realized in the future (FV) into one that can be compared with values in the present (PV). The simplest expression of discounting is given by the following:

$$PV = \frac{FV}{(1 + r)^t}$$

The defining characteristic of this model is the discount rate r. The carbon pricing models used by Auffhammer[60] already have these discount rates incorporated and we applied the 3.0% discount rate to our agricultural calculations.

Restoration costs. Well restoration is accomplished through a private contract, and the costs are often proprietary. As a consequence, there is a lack of public information on its component processes. Reviewing the literature and public records produced a limited number of studies[26,69–71] that act as the foundation of our average estimated restoration cost of US\$8,128 ± 3,131 (mean ± s.d.; US\$, 2018) per well. A more nuanced exploration of these costs is an area for future work.

Sensitivity analyses. We examined how uncertainty affected our benefit–cost ratios for restoration costs, agricultural production, comprehensive ES valuations, social costs of carbon and economic multiplier factors (Fig. 2 and Supplementary Fig. 2). The limited cost estimates ($n = 4$)[26,69–71] correspond to a relatively high degree of variation. We used ±1 s.d. of mean restoration costs as the low and high estimate of this value for the sensitivity analysis. These values are presented on all of the sensitivity analysis figures so as to show how variation in other variables intersect.

Agricultural sales vary annually due to local economic conditions, world agricultural demand and weather. We calculated the mean national sales from the

2008–2018 estimate[72]. The 2017 value used for our county-level estimate (most recent detailed NASS survey)[63] deviated by only 2% from the ten-year mean. To visualize how variation in sales could affect future benefits, we plotted the mean 2008–2018 value ± 1 s.d. over our fifty-year time period.

There are additional ES that can be estimated[73], but location-specific valuations are generally lacking for much of the United States. We used mean values from Moran et al.[3] (for most biomes) and the single peer-reviewed arid/semi-arid estimation[74] to predict the total ES benefits realized over our fifty-year time frame. Although this method gave a more complete valuation for ES, the use of broad biome-level values creates a high level of uncertainty and does not account for unusually high value localities (for example, the agricultural value of California; Supplementary Table 1).

The social cost of carbon is uncertain and subject to debate over appropriate measurement. We used the mean estimated cost per tonne from Auffhammer[60], which assumes a 3.0% discount rate. To measure the effect of the uncertainty in this calculation, we also estimated carbon recovery benefits on the basis of a 2.5% and 5.0% discount and the upper 95% confidence interval from the Auffhammer[60] estimates.

Agricultural markets are one component of the broader macroeconomy, suggesting that growth within this category will have added impact on related markets (that is, economic multipliers). Input–output models estimate the magnitude of these multiplier effects by simulating the impact of economic shocks in one sector through the rest of the economy[75]. The most general standard multiplier relates changes in the total economic output to a change in the output of an individual industry[76]. In agriculture, the output multiplier would take the following form:

$$\text{Agricultural output multiplier} = \frac{\Delta\text{Total economic output}}{\Delta\text{Agricultural output}}$$

There is consensus of substantial positive effects to the surrounding economy from agriculture[77]. To estimate an agricultural output multiplier, we reviewed the economic literature of state-level impact analyses for the agricultural industry. Reviewing 18 studies across the United States[78–95], we found an average multiplier effect of 1.67 (s.d. $= \frac{0.18}{\sqrt{18}} = 0.04$; Supplementary Fig. 2d). Our approach to modelling uncertainty in ES values is consistent with those seen in the ecological economics literature[96].

Data availability

Raw data calculations and ecoregion information are available at Dryad (https://doi.org/10.5061/dryad.ksn02v738). Questions about these data should be directed to the corresponding author. Individual well information is proprietary, but available on subscription to https://www.enverus.com/. Source data are provided with this paper.

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Author contributions
W.H.C., M.D.M. and M.R.M. designed the study. S.V., L.H.L. and V.N. collected data. W.H.C., M.D.M. and M.R.M. designed models, analysed data and were the primary writers. All of the authors edited the manuscript.

Competing interests
The authors declare no competing interests.

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