ECOLOGY

Rural land abandonment is too ephemeral to provide major benefits for biodiversity and climate

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Hundreds of millions of hectares of cropland have been abandoned globally since 1950 due to demographic, economic, and environmental changes. This abandonment has been seen as an important opportunity for carbon sequestration and habitat restoration; yet those benefits depend on the persistence of abandonment, which is poorly known. Here, we track abandonment and recultivation at 11 sites across four continents using annual land-cover maps for 1987–2017. We find that abandonment is largely fleeting, lasting on average only 14.22 years (SD = 1.44). At most sites, we project that >50% of abandoned croplands will be recultivated within 30 years, precluding the accumulation of substantial amounts of carbon and biodiversity. Recultivation resulted in 30.84% less abandonment and 35.39% less carbon accumulated by 2017 than expected without recultivation. Unless policymakers take steps to reduce recultivation or provide incentives for regeneration, abandonment will remain a missed opportunity to reduce biodiversity loss and climate change.

INTRODUCTION

Human populations are in flux around the world, as people seek new economic opportunities in cities and flee changing environments and conflicts in rural areas (*1*). Urbanization and rural outmigration, together with environmental degradation and changing agricultural technologies, have contributed to a growing global trend of cropland abandonment (*2*–*4*). Hundreds of millions of hectares of agricultural lands have been abandoned since 1950 (*5*, *6*). Recent estimates from satellite imagery indicate that as much as 78.5 ± 16.4 million hectares (Mha) of gross cropland abandonment took place globally just from 2003 to 2019 (of which 18.5 ± 3.9 Mha, or 24%, gained tree cover), along with 217.5 ± 37.7 Mha of gross cropland expansion (of which 49% came from the conversion of natural habitats, and 51% from recultivation of abandoned lands or pastures) (*7*). Thus, while cropland expansion remains the dominant threat to biodiversity and carbon stocks (*7*–*9*), many researchers view cropland abandonment as providing a badly needed opportunity to regain natural ecosystems, thereby helping to restore biodiversity (*6*, *10*, *11*), sequester carbon (*12*, *13*), and potentially offset some of the impact of agricultural expansion. Spatial heterogeneity in the distribution of abandonment (and biodiversity and carbon stocks) means that abandonment may have a substantial effect on the biodiversity and carbon stocks of some regions.

This opportunity figures prominently in global scenarios of both future climate change and biodiversity conservation. Nearly all climate scenarios in which global warming is limited to 1.5°C rely on substantial amounts of carbon removal, whether through reforestation, afforestation, or bioenergy with carbon capture and storage (*14*–*16*). Abandoned agricultural lands are seen as ideal places to achieve these carbon removal goals while avoiding competition with food production, particularly by advocates for bioenergy (*4*, *17*). Bioenergy production, however, often precludes the potential for biodiversity gains alongside climate mitigation benefits, because bioenergy plantations are usually poor in biodiversity (though these trade-offs may be reduced in some cases through the use of native perennial species) (*18*). Optimistic scenarios in which biodiversity loss is reversed often rely on forest and grassland regeneration on former agricultural lands (*19*–*21*). Agricultural abandonment is also integral to forecasts of "forest transitions," in which economic development, increasing crop yields, a scarcity of forest products and services, and rural outmigration collectively result in the abandonment of marginal farmlands, allowing a region to transition from net deforestation to net reforestation as regeneration takes place (*22*, *23*).

While abandonment is predicted to continue in Europe, Russia and Central Asia, East Asia, and the Americas (*1*, *15*, *20*), for how long and to what end remains unclear. Moreover, despite recent reforestation in many regions, recent evidence from Latin America has called the durability of such reforestation into question (*24*, *25*). Understanding the true potential of cropland abandonment to contribute to biodiversity and climate goals requires detailed information not only on where and when abandonment is taking place but also on what happens to croplands after they are abandoned. To produce substantial environmental benefits, abandoned lands must stay abandoned long enough to accumulate appreciable amounts of both plant biomass and the species that make up intact ecological communities, a process that can take many decades in order to approach the levels of carbon sequestration or biodiversity typical of intact ecosystems (*26*–*32*). Knowing how long abandonment persists is therefore critical to understanding its potential to help mitigate the ongoing climate and biodiversity crises, yet this question of persistence has received little attention from researchers.

This lack of attention is not entirely surprising because, until recently, it has been difficult to gather detailed information on the duration and long-term trajectories of abandonment. Many existing estimates of abandonment have been inferred by aggregating regional estimates of cultivation, such as country-level FAO (Food and Agriculture Organization of the United Nations) data on cultivated areas, to look for trends over time (*28*, *33*). When derived from satellite imagery, abandonment is most frequently estimated by simply comparing cropland maps for two time points [e.g., 1992 and 2015; (*4*)]. In other cases, maps are made for periods covering

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multiple years [e.g., 4-year epochs; (*7*)]. Annual land-cover time series are becoming more common but are typically limited to a few years [e.g., 2 to 12 years; (*34*–*36*)] or are coarse in resolution [e.g., ≥250 m; (*4*, *35*)]. In addition, most analyses have been restricted to a single region (*37*). These approaches all lack the spatial and temporal detail needed to understand long-term outcomes for abandoned croplands. Moreover, by failing to capture the dynamic patterns of abandonment and recultivation, scientists may substantially overestimate abandonment and the potential for associated environmental benefits (*38*).

Recent advances in remote sensing have made it possible to produce maps of cropland abandonment at both high spatial and temporal resolution. Yin *et al.* (*38*) used a trajectory-based approach to produce accurate maps of annual cropland abandonment at 30-m resolution from 1987 to 2017 with an average overall mapping accuracy of 85 ± 4% (see Materials and Methods). Notably, their approach did not rely on woody revegetation as a proxy for abandonment, thereby allowing for a direct measurement of abandonment at earlier stages of regeneration and across both forest and nonforest biomes.

Here, we use these time-series data (*38*) to quantify the magnitude and persistence of abandonment at 11 sites across four continents (Fig. 1). We address four questions: (i) How long did abandoned cropland stay abandoned on average, and how did this vary among sites? (ii) If we model the persistence of abandonment as a decay process over time, how long did abandoned croplands persist before they were recultivated, and did recultivation (or "decay") rates vary through time and among sites? (iii) How much carbon can accumulate in forests and grasslands as they regenerate in abandoned croplands (in the form of above- and belowground biomass and soil organic carbon, respectively)? (iv) Last, if abandoned croplands had not been recultivated as observed, how much area would have remained abandoned and how much carbon could have been accumulated by the end of our time series? By making use of more accurate and finer-resolution maps for a longer period and a broader set of sites than previous studies, we provide the most detailed analysis to date of the longevity of cropland abandonment. Collectively, our results reveal the temporal nature of cropland abandonment and its potential to sequester carbon and conserve biodiversity.

RESULTS

Abandonment duration

Cropland abandonment was widespread across our 11 study sites (Fig. 2). We found that 8.76 Mha of croplands were abandoned at least once between 1987 and 2017 across our 11 sites (Fig. 3 and fig. S1). (To exclude normal fallow periods, we classify croplands as "abandoned" only when they have not been cultivated for at least 5 years in a row; see Materials and Methods.) This corresponds to 39.84% of the total cropland extent (22.00 Mha) of our sites (i.e., all lands that were cultivated at some point during the time series; see table S1). At individual sites, the area of cropland abandoned at least once ranged from 28.13% (Wisconsin, USA) to 61.05% (Vitebsk, Belarus/Smolensk, Russia) of the total cropland extent (Fig. 3, fig. S3, and table S1), except for Mato Grosso, Brazil, where only 1.32% was abandoned at least once. (Given that land use trends in Mato Grosso were dominated by expansion, not abandonment, we exclude this site from the general results, unless otherwise noted; see detailed results in section S1.2.)

However, we also found that many of these abandoned croplands were recultivated: On average, 38.05% of abandoned cropland area at each site had been recultivated by 2017 (SD = 9.29%; fig. S4). Only 6.06 Mha of croplands remained abandoned as of 2017 across our sites (Figs. 2 and 3), constituting 30.84% less than the area abandoned at least once during the time series (i.e., the potential area abandoned in 2017 in a scenario without recultivation). The magnitude of recultivation varied across sites, with observed abandonment as of 2017 occupying between 13.13% (Shaanxi/Shanxi, China) and 55.38% (Mato Grosso, Brazil) less area relative to the potential area without recultivation at each site (Fig. 3, fig. S5, and table S1). The share of total cropland abandoned also declined by 2017, corresponding

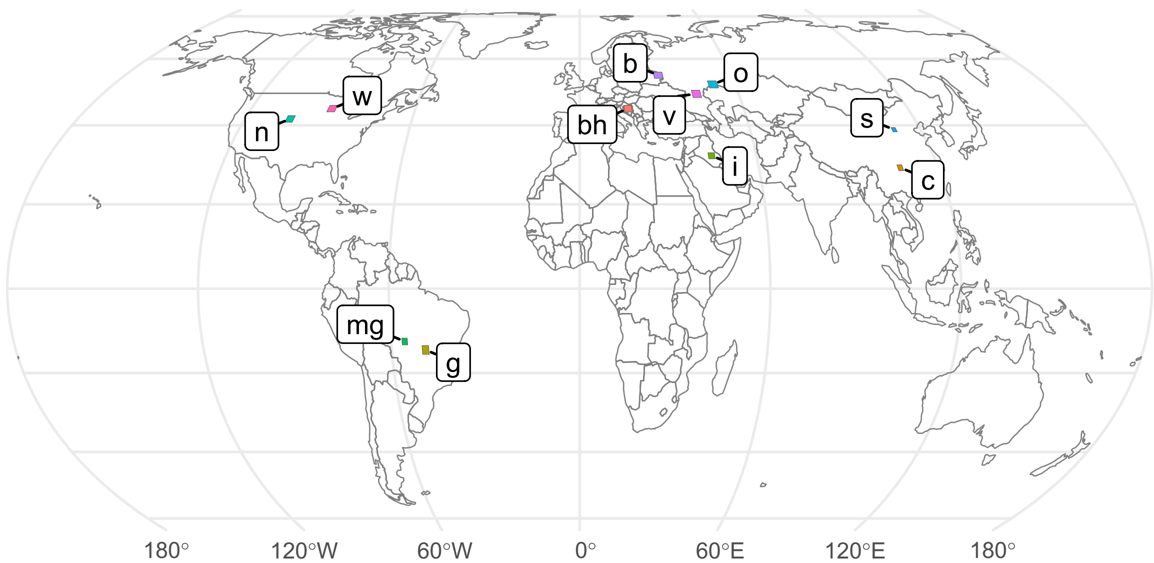

Fig. 1. Site locations. The locations of our 11 sites, from Yin *et al.* (*38*). Sites are labeled as follows: b, Vitebsk, Belarus/Smolensk, Russia; bh, Bosnia and Herzegovina; c, Chongqing, China; g, Goiás, Brazil; i, Iraq; mg, Mato Grosso, Brazil; n, Nebraska/Wyoming, USA; o, Orenburg, Russia/Uralsk, Kazakhstan; s, Shaanxi/Shanxi, China; v, Volgograd, Russia; w, Wisconsin, USA.

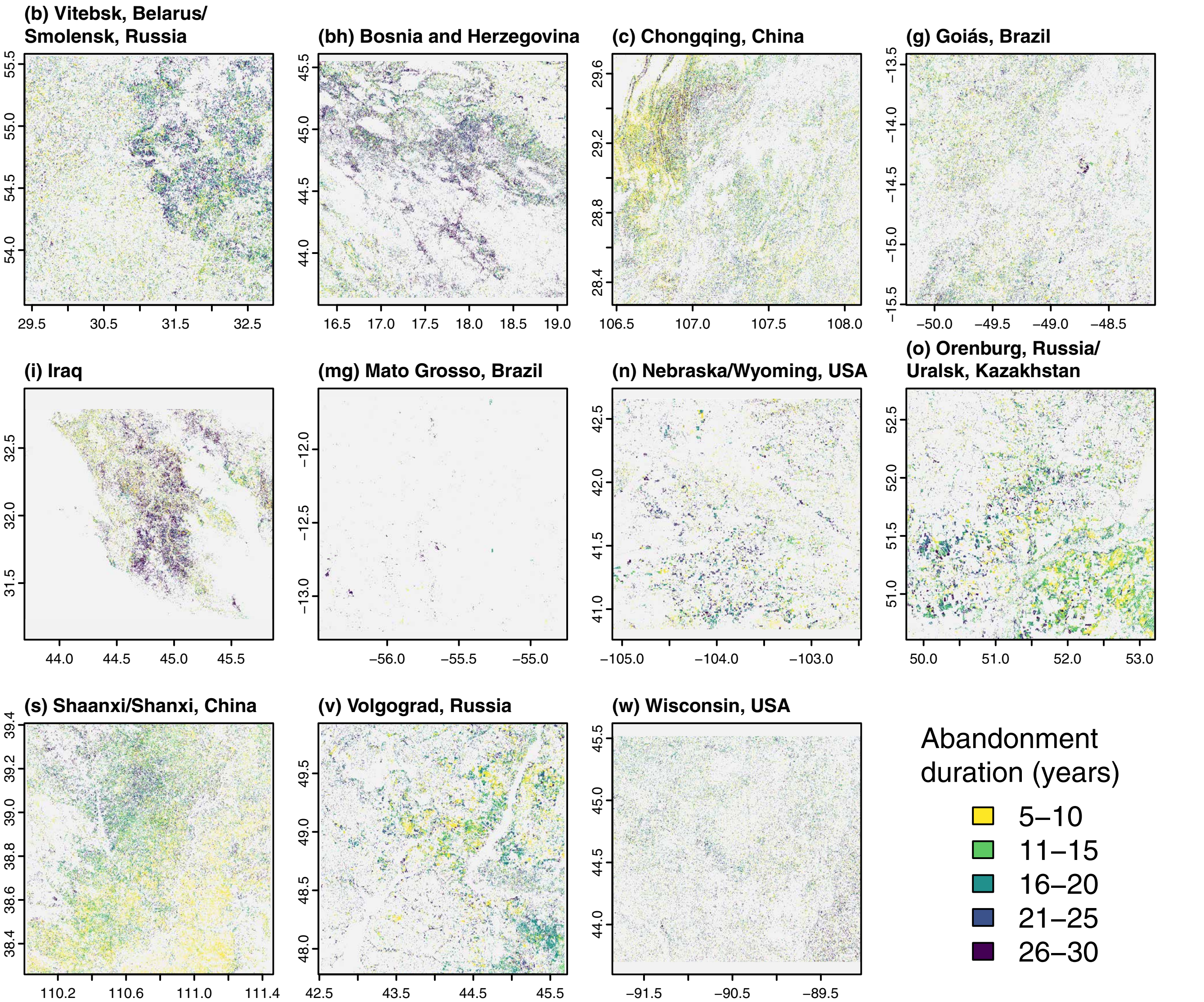

Fig. 2. Spatial patterns of abandonment duration. Observed duration of cropland abandonment (in years) as of 2017 in our 11 study sites. *X* axes show degrees longitude relative to the prime meridian (negative indicating west and positive indicating east), and *y* axes show degrees latitude relative to equator (negative indicating south and positive indicating north). Site locations are shown in Fig. 1, and maps of maximum abandonment duration are shown in fig. S1.

to 27.55% of total cropland extent overall and ranging from 20.8% (Wisconsin, USA) to 47.45% (Bosnia and Herzegovina) at individual sites.

As a result of recultivation, the mean duration of abandonment across all sites was short: 14.22 years (SD = 1.44; see section S1.1), ranging from 12.86 (Orenburg, Russia/Uralsk, Kazakhstan) to 17.57 years (Bosnia and Herzegovina; Fig. 4 and table S2). For comparison, these observed mean abandonment durations were much shorter than the potential durations in our scenario without recultivation, which reached 19.32 years (SD = 2.18) on average across all sites, ranging from 15.70 (Shaanxi/Shanxi, China) to 23.42 years (Mato Grosso, Brazil; fig. S6 and table S3). Compared to their potential values, our observed mean durations declined by between 17.59% (Bosnia and Herzegovina) and 39.34% (Mato Grosso, Brazil). Observed abandonment duration also varied substantially within sites, with the standard deviation in abandonment duration (representing the variation among instances of abandonment at a given site) ranging from 6.93 (Orenburg, Russia/Uralsk, Kazakhstan) to 8.83 years (Mato Grosso, Brazil), for an average of 7.69 years across all sites (table S2 and section S1.1). We also found that recultivation at most sites was usually short term, lasting 6.50 years on average (SD = 3.33), until either the recultivated land was abandoned again and allowed to regenerate or the time series ended. Mato Grosso, Brazil, had a mean recultivation length of 16.25 years, whereas recultivation at the other sites lasted between 4.34 and 6.56 years (fig. S7 and table S4).

Estimated carbon sequestration in abandoned croplands

Using recently published global maps of potential carbon accumulation in forest biomass [1-km resolution; (*31*)] and soil organic carbon [250-m resolution; (*39*)] during natural regrowth of native vegetation, we estimated total carbon accumulation in abandoned croplands as a function of their age and biome (Fig. 5 and table S5).

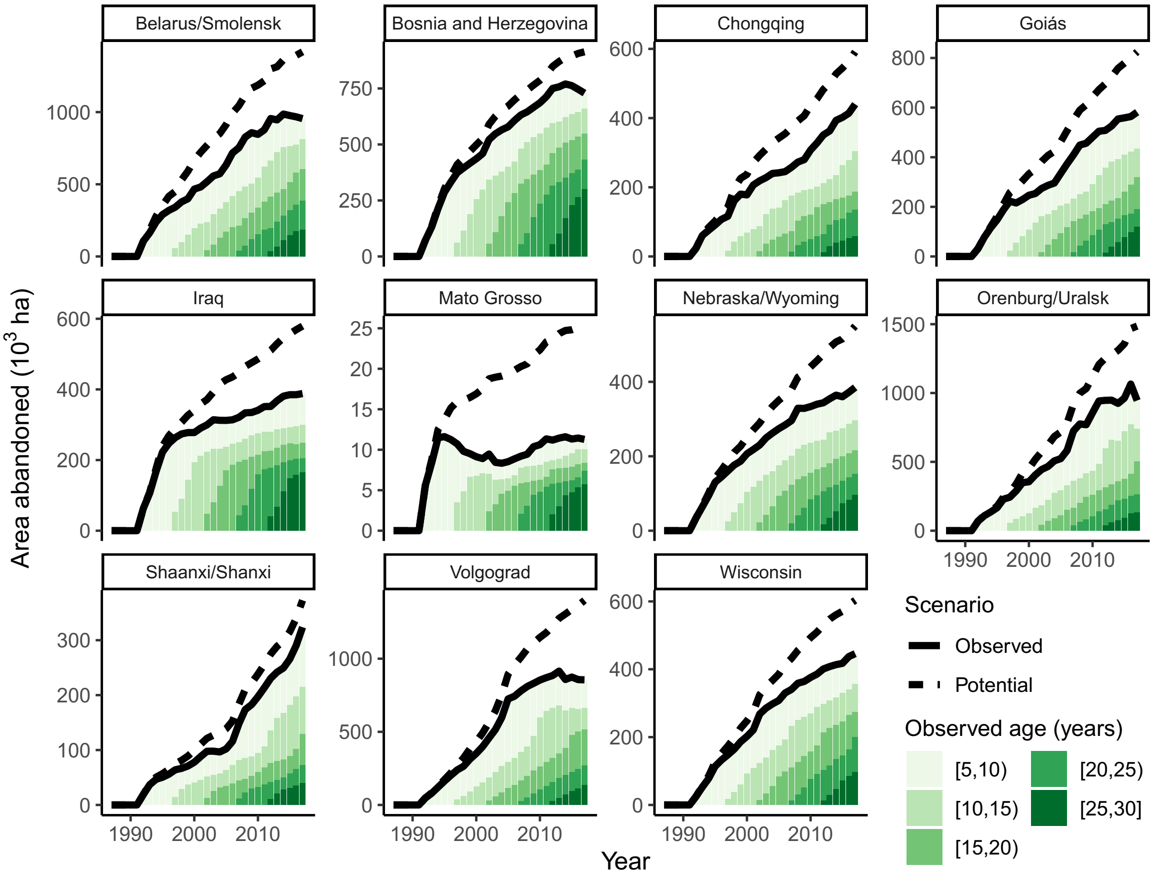

Fig. 3. Abandonment through time. Cumulative area abandoned at each site through time, according to age class (in years). The solid black line represents the total observed area abandoned at each site, and the dashed black line represents the potential area abandoned, assuming a scenario without recultivation. The corresponding area of potential abandonment by age class is shown in fig. S5.

We estimated a total carbon accumulation of 109.83 Tg C (10^6 tons C) total across our 11 sites by 2017. However, this was 35.39% less than the 169.98 Tg C total that could have accumulated in our scenario without recultivation, a scenario in which regrowth was permitted from the time of abandonment through the end of the time series, irrespective of observed recultivation. At individual sites, recultivation reduced estimated carbon accumulation by between 23.23 and 51.32% by 2017 (Fig. 5 and table S5).

Carbon sequestration was not equally distributed across sites (figs. S8 and S9), due partially to differences between sites in the age distribution of abandoned croplands, but more substantially to differences between forest and nonforest biomes (figs. S10 to S12; annual carbon accumulation rates are shown in figs. S13 and S14). Sites in largely nonforest biomes accumulated much less carbon per hectare by 2017 (<3.50 Mg C per ha, on average, at Orenburg, Russia/Uralsk, Kazakhstan; Volgograd, Russia; Nebraska/Wyoming, USA; Iraq; Shaanxi/Shanxi, China) than did sites in forest biomes, which accumulated 28.36 to 48.66 Mg C per ha on average (Wisconsin, USA; Vitebsk, Belarus/Smolensk, Russia; Bosnia and Herzegovina; Chongqing, China; Mato Grosso, Brazil; see table S5 and fig. S15). Goiás, Brazil, which is mostly tropical grassland, savanna, and shrubland with only a small area in forest, had intermediate carbon accumulation per ha, at 9.53 Mg C per ha on average (table S5 and fig. S15).

Modeling recultivation of abandoned croplands

We developed models to predict how long a given pixel of abandoned cropland will remain abandoned before it is recultivated. To do so, we defined a cohort of abandoned cropland as all cropland abandoned in a given year at a given site. We modeled the proportion of each cohort remaining abandoned at each site as a function of time since initial abandonment, which we refer to as "recultivation trajectories" (or "decay trajectories"; see Materials and Methods and Fig. 6). Given that some abandonment periods are inherently limited by the length of our time series (i.e., cropland may remain abandoned beyond the three decades covered by our data), tracking recultivation rates by the year abandoned provides a more accurate estimate of persistence than simply relying on the mean duration of abandonment at each site. These models also allowed us to compare mean recultivation trajectories among sites and explore how recultivation trajectories changed over time at each site. Because the number of observations varies across cohorts, we calculated the mean recultivation trajectory at each site after constraining our data to a range of common "endpoints" (ranging from 10 to 25 years), thereby ensuring that mean values were calculated across a common number of observations for each cohort (see Materials and Methods). We subsequently calculated the half-life, defined as the time required for half of the croplands abandoned in a given year to

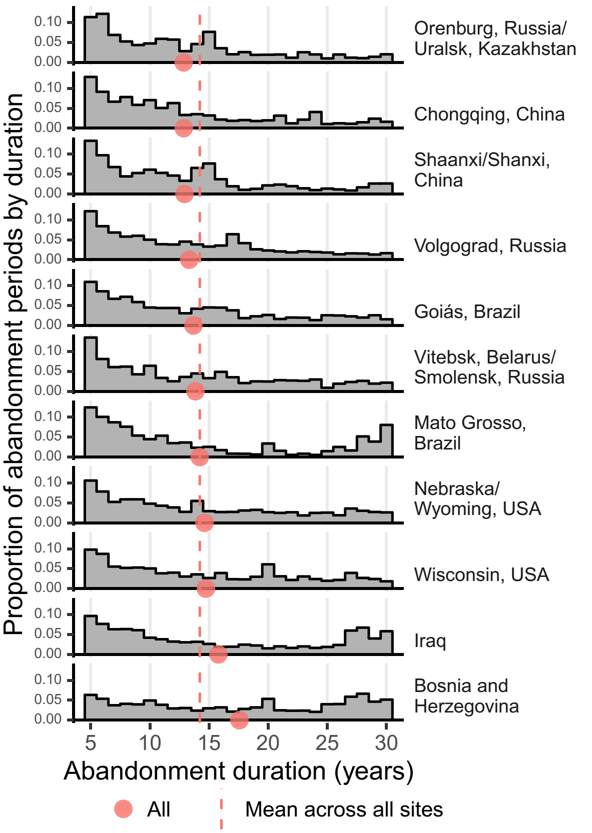

Fig. 4. Distribution of abandonment duration during time series. The distribution of observed abandonment duration (in years) for all periods of abandonment from 1987 to 2017. The *y* axes show the proportion of abandonment periods of a given duration at each site. The red points represent the mean abandonment duration (in years) at each site, and the red vertical dashed line represents the mean of these site-level mean duration values across all sites. Note that these distributions include multiple periods of abandonment for those pixels that experienced abandonment and recultivation multiple times during the time series. See the Supplementary Materials for distributions of the maximum abandonment duration for each pixel (fig. S2), the potential abandonment duration without recultivation (fig. S6), and the duration of recultivation (fig. S7).

be recultivated, based on the mean recultivation trajectory at each endpoint.

Our models show that recultivation happened quickly: They predict that >50% of abandoned croplands will be recultivated within 30 years of initial abandonment at almost all sites (Fig. 7). At all sites except Bosnia and Herzegovina, the half-life ranged from 11.85 to 35.20 years for endpoints between 10 and 25 years (mean ± SD: 22.75 ± 5.27 years; Fig. 7). These half-lives were similar regardless of how widespread abandonment was at each site (fig. S16). Bosnia and Herzegovina, which had the longest mean abandonment duration, was a notable exception. Here, our models predicted much longer half-lives: >50 years for endpoints of 16 years or longer (Figs. 7 and fig. S17). Shaanxi/Shanxi, China, also showed relatively more durable abandonment than other sites, with half-lives of 27.36 to 32.02 years for all endpoints we considered.

In modeling recultivation for each abandonment cohort, we also investigated whether recultivation of abandoned cropland accelerated. Many sites showed recultivation trajectories growing steeper over time (Fig. 6), indicating that abandoned croplands were being recultivated more quickly in more recent years. This is also apparent in Fig. 7, which shows the half-lives declining for shorter endpoints, which incorporate more recent cohorts to a greater extent. This pattern was strongest in Bosnia and Herzegovina, and a linear regression on the half-life confirmed this to be the only site to have a statistically significant and negative rate of change in half-life, whereas more recent cohorts were recultivated more quickly (fig. S18).

DISCUSSION

The degree to which cropland abandonment offers opportunities to sequester carbon and recover biodiversity depends largely on how much farmland is abandoned and how long it stays abandoned. Using a new annual land-cover time series, we uncovered high levels of cropland abandonment across 11 sites in diverse biomes on four continents (Fig. 2). However, by tracking abandonment from year to year, we showed that a large portion of this abandonment was ephemeral (Figs. 3 and 4). Previous estimates of the amount of cropland abandoned based on just two points in time [e.g., a global estimate of 83 Mha between 1992 and 2015 in (*4*)] likely underestimate abandonment by excluding any new cultivation and subsequent abandonment that takes place between the chosen time points. Two–time point estimates almost certainly overestimate the amount of persistent abandonment, due to a failure to exclude short-term fallow periods and, as our analysis shows, high rates of recultivation. Had we estimated "abandonment" based on cultivation at only two points in time (1987 and 2017), we would have found 17.49% less abandonment as of 2017 (with even greater variation at individual sites), the inclusion of substantial amounts of abandonment that did not meet our 5-year abandonment definition, and low spatial agreement between areas identified as abandoned (table S6 and section S1.5).

Our results also demonstrate the value of considering the dynamics of abandoned croplands as a function of time since abandonment, rather than relying only on the average durations observed during a time series. This is most apparent in Shaanxi/Shanxi, China: Although this site had one of the shortest mean abandonment durations (because most abandonment took place toward the end of the time series; fig. S19), it also had some of the longest half-lives of any of our sites (consistently ~30 years; Fig. 7 and fig. S17). Therefore, our modeled recultivation trajectories indicate that abandonment may be longer-lasting at this site than initially demonstrated by the abandonment periods we observe during our time series. By modeling recultivation as a function of the time since initial abandonment, we estimate that half of the croplands abandoned in a given year will be recultivated within 10 to 30 years at almost all of our sites (fig. S17). These modeled decay rates portray a dynamic process, where abandonment is rarely a final stage but rather part of a cycle of turnover on decadal time scales (*33*), with strong implications for the biodiversity and climate opportunity of abandonment.

The impermanence of abandonment that we observed generally matches the findings of the small number of comparable case studies that have considered this issue (*12*). To the best of our knowledge, only one other study used an annual time series to investigate agricultural abandonment (*37*). That 1991–2017 study of a grassland region of northern Kazakhstan observed abandonment of about 40.5% of cultivated areas, and subsequent recultivation of about 20.0% of that abandonment. This recultivation rate was similar to our most persistent site (Shaanxi/Shanxi, China, 19.88%), but was much lower than our average recultivation rate across sites

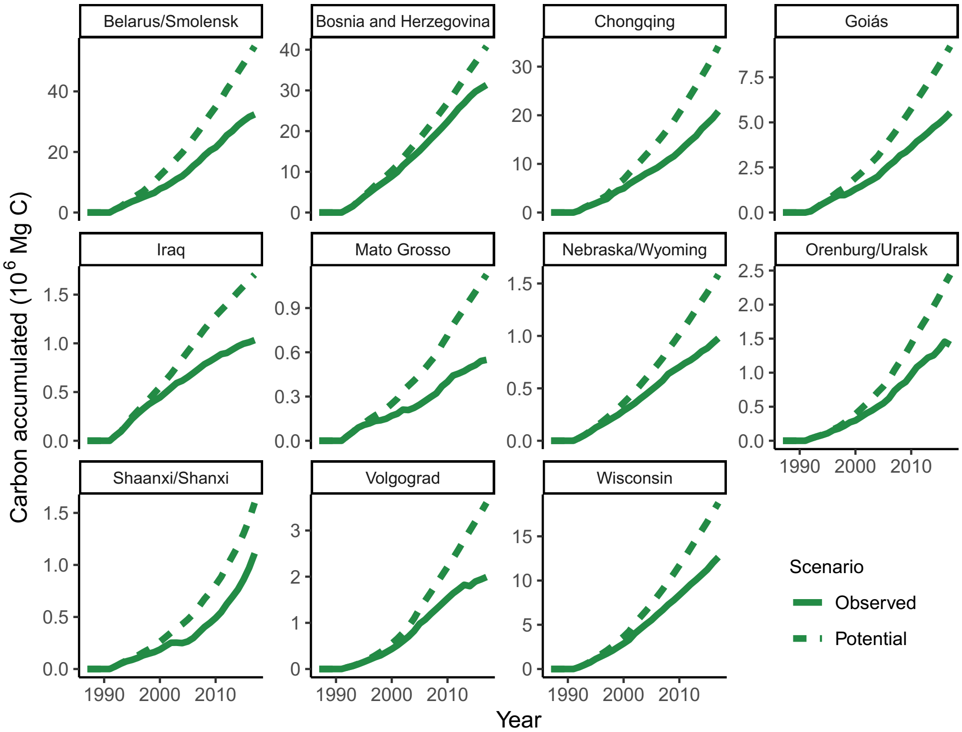

Fig. 5. Carbon accumulation following abandonment. Cumulative carbon accumulation in abandoned croplands over time, in terms of millions of Mg C (10^6 tons C). The solid green line represents the total observed carbon accumulation at each site, and the dashed green line represents the potential carbon accumulation, assuming a scenario without recultivation.

(38.05%), and lower still than our two sites closest to the region of Kazakhstan studied by (*37*): Orenburg, Russia/Uralsk, Kazakhstan and Volgograd, Russia, which had higher recultivation rates of 43.2 and 45.41%, respectively (fig. S4).

Our projected half-lives were similar to those found in a study from Costa Rica [≤20 years; (*40*)], but longer than in other parts of the Neotropics, where empirical evidence indicates that secondary forest regeneration is often very short-lived (*12*, *24*, *41*, *42*). Secondary forests were cleared and recultivated even more quickly in the Brazilian Amazon (50% within 5 to 8 years), where 80% of secondary forests were ≤20 years old (*12*, *41*, *42*). Across the tropics, only 33% of forests regenerating on sites that had been recently cleared were ≥10 years old (*43*). However, these differences may be the result of (i) a time delay between abandonment and sufficient regrowth of secondary woody vegetation to be detected by satellites, (ii) our exclusion of abandonment of less than 5 years to avoid confusion with normal fallow periods, or (iii) our models of recultivation for each cohort, which eliminate the influence of the time-series length and lengthen abandonment estimates.

Implications for biodiversity recovery

Our results show that most cropland abandonment is ephemeral, contrary to optimistic assumptions (*4*, *17*), and that even sites with the most persistent abandonment are unlikely to retain large areas where natural vegetation is allowed to regenerate for ≥50 years. Thus, the recultivation of abandoned croplands comes with substantial trade-offs (*44*), and the high recultivation rate we observed will markedly limit the scope for abandoned croplands to play a major role in carbon sequestration or the recovery of biodiversity.

Even under optimal conditions, recovery of natural ecosystems requires time, typically multiple decades, in order for locations to recover species richness approximating that found in reference systems (*6*, *27*–*29*, *45*, *46*). Species richness values for rarer, forest-adapted, or old-growth–dependent species recover even more slowly. When recovery toward old-growth ecosystems is measured in terms of community composition, species similarity, and vegetation structure, it can take much longer than when measured simply by the recovery of total species richness or abundance (which can be dominated by widespread generalist species) (*45*, *47*, *48*). In chronosequences, lowland Neotropical forests recover quickly in terms of tree species richness (reaching 80% of old-growth levels after 20 years and 90% after 31 years), but much more slowly in terms of tree species composition (34% of old-growth levels after 20 years, requiring 487 years to reach 90%) (*26*). Furthermore, these estimates may be overly optimistic, due to positive site selection bias (*46*), especially if the area around fast-recovering sites retained relatively high forest cover [76% on average in (*26*)]. Recovery is likely to be much slower in heavily deforested landscapes.

Faunal recovery also typically takes a long time, at least for most groups of vertebrates. Across tropical forests, amphibian, bird, mammal, and reptile species richness largely recovers within 40 years, but species compositional similarity for these groups takes much longer to recover (if at all), particularly for late-successional species, insectivorous birds, and forest specialists (*27*). No vertebrate groups reach species compositional similarity to reference old-growth forests, even in the oldest secondary forests (30 to 65 years) (*27*). There is, however, substantial variability in how quickly and how completely ecosystems recover following disturbances and abandonment

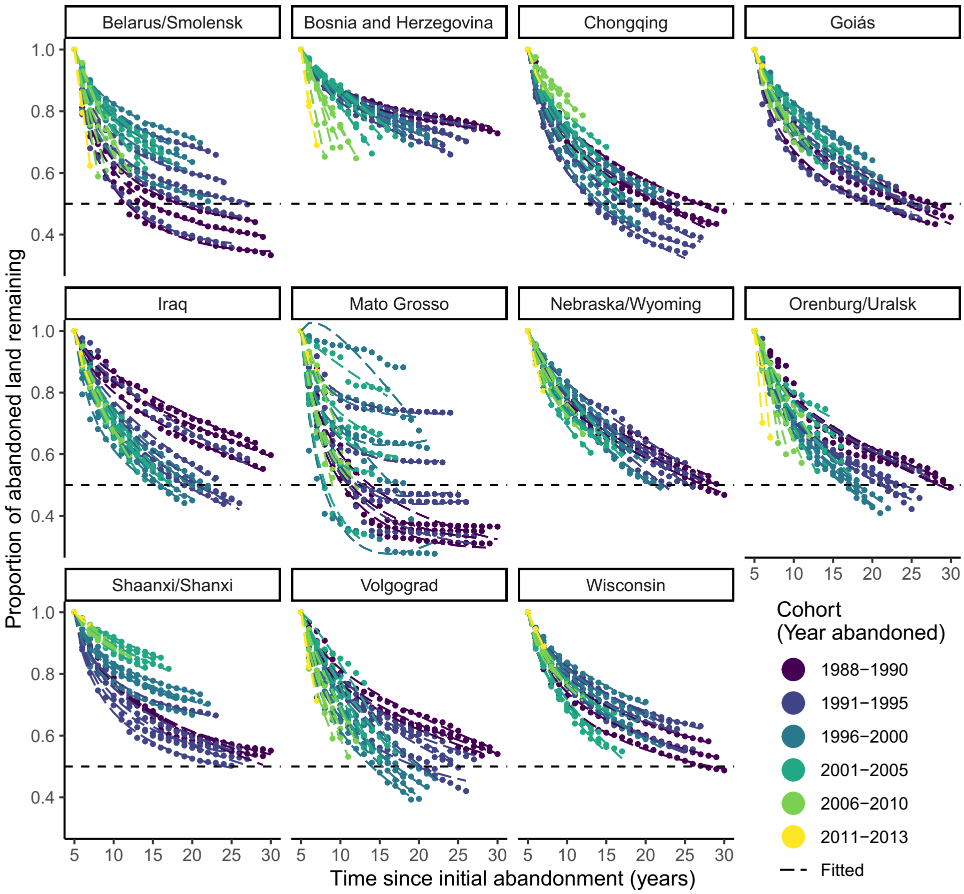

Fig. 6. Recultivation of abandoned croplands. Modeled recultivation (decay) trajectories showing the proportion of each cohort of abandoned land (i.e., all pixels abandoned in a given year) remaining abandoned over time for each of our 11 sites. Points represent actual observations by cohort, and dashed lines represent linear model predictions for each cohort as a function of time (including a linear and logarithmic term of time). Colors of both points and dashed lines correspond to roughly 5-year group of cohorts, ranging from dark purple (oldest cohorts) to green and yellow (most recent cohorts). The horizontal black dashed line shows a proportion of 0.5, indicating the point where half of a cohort has been recultivated. Model diagnostic plots are shown in fig. S28.

(*46*–*49*). Natural regeneration is likely to progress more quickly and successfully under the right conditions, especially after low-intensity disturbances (e.g., selective logging) and when there are relatively undisturbed or mature ecosystems nearby to act as propagule sources (*30*, *47*, *48*). Recovery can also be rapid for certain animal groups in specific cases [e.g., birds and dung beetles in the Colombian Andes; (*30*)], but these are the exceptions rather than the rule.

Grassland ecosystems can sometimes recover more quickly following disturbances than forests (*50*), but not often (*28*, *29*). Yet, even after full recovery of species richness (with minimum estimated recovery times of >100 years), compositional similarity of secondary grasslands to undisturbed grasslands remains low (43%) (*29*). For example, Minnesota (USA) grasslands showed quick initial gains in biodiversity following abandonment, but thereafter, both biodiversity and productivity increased slowly, reaching only 73% of the diversity and 53% of the productivity levels of the reference ecosystem after 91 years (*28*). Similarly, Eurasian grasslands, where widespread conversion and subsequent abandonment have occurred, showed increases in biodiversity in older abandoned fields, yet still had not fully recovered with respect to either plant species richness and community composition (*51*) or bird species richness and diversity (*52*) after 24 and 18 years of observation, respectively.

Carbon accumulation in abandoned croplands

Abandoned croplands will achieve only a small fraction of their carbon storage potential if abandonment lasts only a couple of decades. Despite relatively quick accumulation of carbon in aboveground biomass in forests during the first few decades of regeneration, it can take between 50 and 100 years for secondary forests to achieve similar levels of biomass to old-growth forests (*32*, *53*). For example, studies have shown that Neotropical aboveground forest biomass on abandoned cropland reached 90% of old-growth forest biomass after a median of 66 years, but biomass remained at only 50% of old-growth levels after 20 years (*32*). Furthermore, carbon accumulation estimates vary widely by biome and by prior land use.

Our estimates of carbon accumulation in both forest biomass and soils as a function of time and biome confirmed that while abandoned croplands hold substantial potential to accumulate carbon over time (109.83 Tg C total by 2017 across our sites), they only accumulated 64.61% of their potential as a result of recultivation, even when that potential is only estimated over our relatively short time series. While a 35.39% loss is not as large as has been noted in another recent study of ephemeral forest regeneration (*54*), which estimated forest carbon accumulation of 70% less than the potential maximum if no secondary forests were recleared, this lost opportunity is nonetheless considerable.

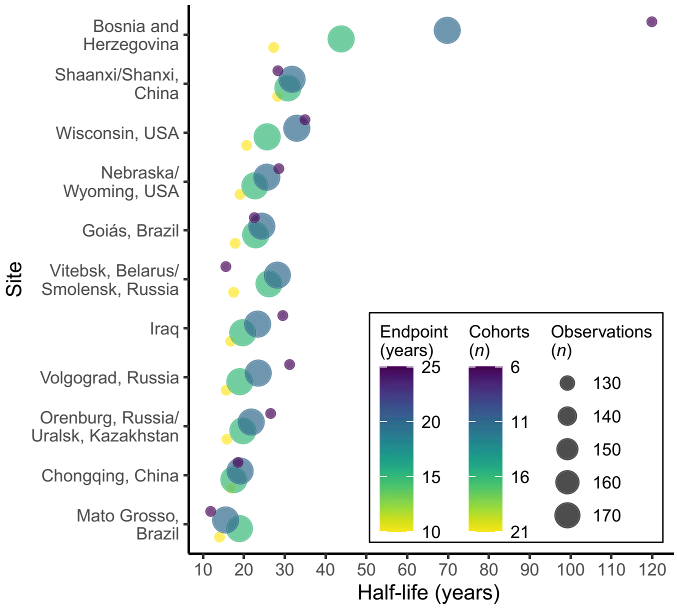

Fig. 7. Half-life of abandonment. Mean half-lives of abandoned croplands at each site, calculated across a range of common endpoints. To make fair comparisons across cohorts with varying numbers of observations, we subset our data to a range of common endpoints (e.g., 15 years), restricting cohorts to the same number of observations. For each endpoint, we then calculated the mean trajectory across cohorts that meet the endpoint threshold and used these mean trajectories to calculate the half-life (i.e., the time required for half of a cohort to be recultivated; see Materials and Methods). See fig. S17 to see half-lives for the full range of endpoints.

Abandoned croplands in forested biomes showed a much higher carbon accumulation, and correspondingly higher opportunity costs of recultivation, than abandoned croplands in grassland biomes (table S5 and fig. S11). While grasslands can also harbor substantial amounts of carbon sequestered in soils (*55*), grassland soil carbon may accumulate even more slowly than aboveground forest biomass, taking a century or longer to return to reference levels (*13*). For example, studies have shown that while abandoned croplands across Russia accumulated a total of 13.20 Mg C/ha in the top 5 cm of soil on average during the first 20 years following abandonment, these fields still had significantly less carbon sequestered than reference grasslands after 24 years of observation and were expected to take >60 years to recover to reference levels (*56*). Here, we estimate accumulation of only 1.49 to 3.43 Mg C per ha by 2017 on average (table S5) at our predominantly grassland sites—only a fraction of the total observed by (*56*), largely a result of the short abandonment lengths at these sites.

Study limitations

We note several limitations to our work here. First, multiple factors beyond the duration of abandonment will affect outcomes with respect to both biodiversity and carbon. For example, the fact that these lands were being used for agriculture can impede full achievement of carbon or biodiversity goals, given the impact of soil erosion and other abiotic (e.g., residual pesticides and excess nutrients) and biotic (e.g., invasive species) legacies associated with farming (*28*, *45*, *48*, *57*). A lack of nearby source populations in heavily disturbed landscapes can hinder recolonization by plants and animals, thereby affecting both biodiversity and carbon sequestration, as can climate change or the loss of natural disturbance regimes (*48*, *58*, *59*). While natural regeneration is typically cheaper than active restoration, it is not clear that natural regeneration outperforms active restoration on abandoned croplands. Meta-analyses suggesting that natural regeneration outperforms active restoration have suffered from site-selection biases, in that sites that did not regenerate naturally were not included, whereas examples of unsuccessful active restoration were (*46*). In addition, more heavily altered systems typically require active restoration approaches such as invasive species control or translocation of plants and animals, and experience longer recovery times (*13*, *30*, *45*, *48*).

Grassland regeneration is particularly challenging, because many grasslands require natural disturbance regimes (e.g., grazing or fire), which may be absent following abandonment (*29*). Without such disturbances, grassland biodiversity can be lost if low-intensity farmlands are abandoned, particularly when historically unforested ecosystems are colonized by woody vegetation (*2*, *29*, *60*, *61*). This is especially the case in Europe, where many remaining species of conservation concern are dependent on low-intensity farmland—a product of both cultural preferences and a very long history of cultivation (*62*). Although we focus here on the potential for abandonment to benefit biodiversity through the long-term regeneration of native vegetation, there may be cases where long-term regeneration may run counter to conservation goals, in which active intervention and management (through grazing, hunting, or otherwise) may be necessary to maintain grasslands and other high-biodiversity habitats such as wetlands (*2*, *11*).

Second, our sites were specifically selected on the basis of documented abandonment. Thus, while our results are likely representative of areas that have experienced substantial abandonment, they are not a representative sample of the entire globe, and they focus on regions with more cropland abandonment than the global average. Nevertheless, because these abandonment hotspots hold the greatest potential to provide associated environmental benefits, it is precisely in these places that our findings will have the greatest implications. Therefore, these data represent a unique opportunity to study the long-term outcomes of cropland abandonment. However, there is some indication that abandonment may be more durable in Europe, another region that has experienced significant abandonment (*11*, *35*). A recent review of post-abandonment trajectories in Europe found that in most cases (64.44%, or 87 of 135 studies reviewed), abandoned lands went through secondary succession and transitioned toward seminatural landscapes, although Eastern Europe and Russian abandonment may be more prone to recultivation (*63*). This study did not include time since initial abandonment as a factor, however, and the differences in abandonment persistence between regions merit future investigation.

Policy implications

Harnessing abandonment as an environmental opportunity will require an understanding of the drivers of abandonment and recultivation. Abandonment is certainly related to agricultural suitability (*64*), but it is also driven by a combination of socioeconomic and demographic changes, policies, and broader environmental factors (*3*, *44*, *64*, *65*). Abandonment is often a by-product of urban migration and rural depopulation, particularly in Europe, East Asia, and Latin America (*2*, *25*). Other cases are more directly related to sociopolitical change. For example, the collapse of the Soviet Union triggered large-scale abandonment in Eastern Europe, especially in less productive areas that had been supported by state subsidies (*34*, *35*, *44*, *66*). While studies have shown that economically marginal lands like these are less likely to be recultivated on the whole than more productive lands (*44*, *67*), our data show that our three former Soviet sites (Orenburg, Russia/Uralsk, Kazakhstan; Volgograd, Russia; and Vitebsk, Belarus/Smolensk, Russia) experienced some of the highest recultivation rates and shortest half-lives. In northern China, on the other hand, abandonment (and reforestation) was encouraged through one of the world's largest reforestation schemes, the "Grain for Green Program" (also known as the Sloping Land Conversion Program), which provides financial incentives to reforest croplands for erosion control and other forest-related ecosystem services (*68*). We found relatively durable abandonment in Shaanxi/Shanxi, China, a site with some of the most consistently long half-lives. The persistence of abandonment in this region, however, will depend on the consistency and continuity of national land use policy (*69*). Recultivation may occur when incentives for reforestation are removed (*69*) or when subsidies for cultivation are reestablished (*44*). Recultivation can also be triggered when short-term stressors are removed, as is frequently observed in post-conflict regions (*65*, *70*), or when international or rural-urban migration pathways are disrupted, as has recently occurred between Latin America and the United States (*25*). Our research demonstrates the value of long-term analysis at annual intervals, which has the potential to improve our understanding of the drivers of abandonment and recultivation.

Even once abandonment occurs, there are many socioeconomic and political barriers that can hinder habitat regeneration in abandoned croplands. These include policies that obligate farmers to cultivate land, a lack of incentives to protect and foster regenerating habitats, and, perhaps most importantly, negative cultural perceptions of abandonment and the "messy" landscapes that result (*6*). The loss of certain types of landscapes or rural ways of life can cause emotional distress and regional economic upheaval, which, in turn, can spur efforts to avoid or reverse abandonment (*2*, *5*, *33*, *44*). Behavioral research also highlights the importance of social factors such as corruption, political and institutional support, and demographic changes in driving decisions to abandon or recultivate cropland, alongside the more obvious biophysical and economic conditions (*71*).

For abandoned croplands to reach levels of carbon stocks and biodiversity comparable to more intact natural ecosystems, they should, in general, persist for >50 years (*13*, *26*–*29*, *32*), which is at least three decades longer than the mean length of abandonment we observed. Without new policies and incentives to discourage recultivation, abandoned areas are unlikely to provide meaningful biodiversity and carbon benefits, despite their considerable potential and expected importance for meeting both climate and biodiversity goals. When recultivation occurred, its duration was relatively short (fig. S7). These short recultivation periods may partly be a function of when recultivation took place (by our definition, it must follow at least 5 years of abandonment), but they could also be a sign that these croplands are marginal economically. In this case, taking them out of production for longer periods of time is unlikely to seriously affect overall food supplies.

Encouraging the persistence of abandonment, especially on marginal croplands, could be achieved by designating abandoned fields as protected areas, by incorporating natural regeneration into payments for ecosystem service programs to allow landowners to benefit economically from abandoning their croplands, or by taking steps to support sustainable long-term cultivation of some sites, thereby reducing turnover among fields that have previously been part of long-term fallowing cycles (*44*). The relative durability of cropland abandonment in Shaanxi/Shanxi Province provides some evidence that incentive programs designed to restore or reforest cropland for long periods of time can be successful. This is encouraging, yet there continues to be a need to improve the biodiversity outcomes of such programs, many of which prioritize the planting of nonnative forests at the expense of local biodiversity, ecosystem stability, and local livelihoods (*68*). More alarming, however, are recent studies that indicate that some large-scale reforestation programs fail to provide either environmental or livelihood benefits; this may especially be the case when nonforested biomes are targeted for afforestation, or when programs fail to take into account the local socioeconomic context (*72*). Clearly, more research is needed to improve the outcomes of such programs, and we stress that any policies should be developed jointly with local communities to address trade-offs between biodiversity, carbon storage, and livelihoods. Our results make one thing clear: If cropland abandonment continues to be as short-lived as we have shown here, the large potential benefits of regenerating habitats for both carbon storage and biodiversity conservation will remain an untapped opportunity.

MATERIALS AND METHODS

Abandonment maps

We use annual land-cover maps with a 30-m resolution from 1987 to 2017 (*38*), derived from publicly available Landsat satellite imagery, mapping four land-cover classes: (i) cropland, (ii) herbaceous vegetation (e.g., grassland), (iii) woody vegetation (e.g., forests), and (iv) nonvegetation (e.g., water, urban, or barren land) (fig. S20). Our 11 sites were mapped with high accuracy (average overall accuracy, 85 ± 4%) and provide broad coverage of different continents and ecosystems (site locations are shown in Fig. 1, and site ecoregions and biomes are shown in figs. S10 to S12 and section S1.3). We focused exclusively on cropland abandonment, because pasture abandonment is very difficult to discern from satellite imagery and is not captured in our data.

We selected our study areas to analyze abandonment in a wide range of biomes from drylands (Iraq; Nebraska, USA; Shannxi/Shanxi, China; and Orenburg, Russia/Uralsk, Kazakhstan), to temperate regions (Vitebsk, Belarus/Smolensk, Russia; Bosnia and Herzegovina; Volgograd, Russia; Wisconsin, USA), to the subtropic and wet tropics (Chongqing, China; Goiás, Brazil; and Mato Grosso, Brazil; see section S1.3). Furthermore, Yin *et al.* (*38*) selected these regions because of their documented histories of cropland abandonment in the past three decades, to develop a method that can accurately map abandonment at high spatial and temporal resolution. Our study regions also captured a diverse mix of three potential abandonment drivers including sociopolitical (e.g., Shannxi/Shanxi, China, and Bosnia and Herzegovina), economic (e.g., Chongqing, China), and environmental change (e.g., Iraq). Here, we use data for 11 of the 14 areas originally mapped by Yin *et al.* (*38*), dropping three sites (Sardinia, Nepal, and Uganda) because of low map accuracy (classification accuracy for abandonment < 0.4). Accordingly, while our study sites are not a representative sample for the globe, they are likely representative of those areas that have recently experienced abandonment, and present a unique opportunity to understand the issue of abandonment.

Defining abandonment

Differentiating abandonment from short-term fallowing or crop rotations is difficult because agricultural practices can vary widely by region, and studies use many different definitions (*38*). Here, to exclude short-term fallowing, we define abandonment as cropland that is no longer under active cultivation, is left free of direct human influence (e.g., is not converted to urban land use), and remains so for at least five subsequent years, following FAO (*73*). Recognizing that longer abandonment thresholds may be more appropriate in certain contexts, we performed a sensitivity analysis by varying our abandonment definition (section S1.4) and found that, as expected, longer definitions resulted in less abandonment overall, longer average abandonment durations (fig. S21), and lower recultivation rates (fig. S4). However, even when only considering abandonment ≥10 years, we still observed between 11.91 and 30.13% recultivation across our sites (in Shaanxi/Shanxi, China and Volgograd, Russia, respectively), suggesting the reliability of our abandonment definition. We defined an abandoned pixel as "recultivated" if it was subsequently classified as cropland for 1 year or more because even a single year of recultivation restarts the regeneration process. Similarly, we assessed how different thresholds of recultivation affected the mean duration of recultivation (fig. S22), in addition to the extent to which recultivation depends on abandonment threshold (fig. S4).

Data processing

We processed and analyzed abandonment map data in RStudio version 2021.9.2.382 (*74*), using R version 4.1.2 (2021-11-01) (*75*), primarily with the terra (*76*), data.table (*77*), and tidyverse (*78*) packages.

We identified periods of cropland abandonment by tracking each pixel's land cover through time to identify signs of land-cover changes that indicated transitions between active cropland use (i.e., cultivation) and subsequent inactivity (i.e., left fallow or uncultivated). We first implemented 5- and 8-year moving window temporal filters to smooth land-cover trajectories and remove land-cover changes that are temporally unlikely (section S2.1). Together with our 5-year abandonment threshold, these temporal filters address very short-term misclassifications that might otherwise appear like recultivation.

We classified a pixel as abandoned anytime it transitioned from cropland to either herbaceous or woody vegetation (collectively referred to as "noncropland") and subsequently remained classified as noncropland for five or more consecutive years (see section S2.2 for full details). We considered an abandoned pixel to be "recultivated" when it transitioned from noncropland back to cropland for 1 or more years. Pixels that transitioned from cropland to the nonvegetation class were not considered abandoned and were excluded from our analysis. Nonvegetated land consisted of <10% of total site area in all sites except Shaanxi/Shanxi, China (12.7%) and Iraq (52.8%) and remained stable or declined over time in all 11 sites.

Calculating observed and potential abandonment duration

We calculated abandonment duration as the number of years that elapsed between the initial transition from cropland to noncropland and either recultivation or the end of the time series. Because our abandonment definition only considers croplands that have been abandoned for five or more contiguous years, the minimum abandonment duration is 5 years. Because a pixel may be abandoned and recultivated multiple times throughout the time series, we calculated the mean abandonment duration in two ways: (i) across all periods of abandonment (Fig. 4) and (ii) across only the longest period of abandonment experienced by each pixel (figs. S1 and S2). Using a similar method, we also tracked the duration of recultivation periods that followed periods of abandonment (fig. S7).

To understand the opportunity cost of recultivation, we also developed a simple scenario assuming that no recultivation took place during our time series. This scenario assumed that all abandoned croplands remained abandoned from their initial abandonment through the end of the time series. We calculated the area abandoned in each year according to age (i.e., time since initial abandonment) and used this to calculate potential carbon sequestration (see below). Potential area abandoned without recultivation is shown as a dashed line in Fig. 3.

Estimating carbon accumulation in abandoned croplands

We estimated carbon sequestration in abandoned croplands using recently published maps of annual carbon accumulation rates during secondary succession. For forest biomes [delineated using the Ecoregions2017 map (*79*); see fig. S10 and section S1.3], we applied rates from (*31*), which provides annual carbon accumulation rates for the first 30 years of natural forest regrowth in terms of aboveground biomass, belowground biomass, and soil carbon (which we subsequently combined). For nonforest biomes (e.g., grasslands and savannas; see fig. S10), we conservatively assumed that most of the ecosystem carbon is stored in soils (*80*) and therefore used soil organic carbon (SOC) sequestration as a proxy for potential carbon sequestration. We applied annual SOC sequestration rates estimated from the recently published Soils Revealed database (*39*), which includes estimates of potential SOC stocks in former agricultural lands as they return to native vegetation after 20 and 80 years. We extracted only pixels representing transitions from cropland to native vegetation and calculated the mean SOC stock for former croplands at each of our sites after 20 and 80 years of regeneration (see more details in section S2.3). We used these two mean SOC stock estimates to calculate annual SOC sequestration rates for years 1 to 20 and 21 to 80 of regeneration. These SOC sequestration rates were then combined with our forest carbon accumulation rate layer and applied to our abandonment age data to calculate potential forest and soil carbon accumulation during the duration of abandonment.

Maps showing the combined forest and SOC sequestration rates are shown for years 1 to 20 in fig. S13 and years 21 to 80 in fig. S14. Total and potential carbon accumulation at each site by 2017 is shown in figs. S8 and S9, respectively. Maps of forest and soil carbon accumulation rates were resampled from their original resolutions (1 km and 250 m, respectively) to match the 30-m resolution of our land-cover maps.

Modeling abandonment recultivation (or decay)

Because some abandonment periods are limited by the length of the time series (potentially causing some observed periods of abandonment to end before they are truly recultivated), we modeled recultivation of abandoned croplands as a function of time since initial abandonment. We tracked recultivation (decay) by calculating the proportion of each cohort of pixels abandoned in a given year that remain abandoned in each year following abandonment. We parameterized a linear model predicting the proportion of abandoned cropland in each cohort at each site remaining abandoned as a function of time since initial abandonment (decay trajectories). We tested a range of model specifications, including linear and log transformations of both proportion and time, and multiple time predictor terms. We included both cohort and site-level fixed effects, fitting unique coefficients for each cohort at each site in a single linear model for all data pooled across sites.

We selected the highest performing model based on Akaike information criterion values (fig. S24). For cohorts of abandonment initially abandoned in years y = 1988, …,2013, our model predicted the proportion p of each cohort y at site z remaining abandoned as a function of time t (i.e., the number of years following initial abandonment), with one log-transformed and one linear term of time (Eq. 1)

$$p_{\mathrm{yz}} = 1 + \beta_{\mathrm{yz},1} \log(t+1) + \beta_{\mathrm{yz},2}\, t \qquad (1)$$

where $\beta_{yz,1}$ and $\beta_{yz,2}$ represent the regression coefficients on the log and linear terms of time t, respectively, for cohort y at site z. Model assumptions were tested through visual inspection of diagnostic plots (fig. S28; full details in section S2.4). The observations and fitted values from our pooled linear model are shown in Fig. 6, and all individual model coefficients are shown in fig. S25.

Because of the nature of our time series, each cohort has a different number of observations (corresponding to the number of years between the year of initial abandonment and the end of the time series), complicating efforts to compare cohorts and calculate mean trajectories across cohorts at each site. To address this issue, we developed an approach to parameterize our linear model using subsets of data restricted to common endpoints (e.g., 15 years) such that each cohort had the same number of observations. For example, for a given endpoint of 15 years, we included only those cohorts with at least 15 years of observations and also excluded all observations beyond 15 years for cohorts that met the 15-year threshold. We then parameterized our linear model with this subset and calculated mean log and linear coefficients across cohorts at each site, from which we then calculated the time required for half of the abandoned cropland at each site to be recultivated ("half-lives").

We repeated this analysis for the full range of possible common endpoints that included more than one cohort (7 to 29 years). Half-lives for a few select endpoints (10, 15, 20, and 25 years) are shown in Fig. 7, and model results for these subsets and their corresponding mean decay trajectories are shown in figs. S26 and S27. Half-lives for all modeled endpoints (7 to 29 years) are shown in fig. S17.

This method for modeling half-lives based on common endpoints allows us to draw fair but conservative comparisons across cohorts, without assigning disproportionate weight to cohorts with fewer observations. We prioritize intermediate endpoints in our reporting of the results for two reasons: Longer endpoints are biased toward older cohorts (by excluding more recent abandonment), and while shorter endpoints incorporate a more complete set of cohorts, they make use of fewer observations overall and place relatively more weight on the initial stages of abandonment. As a result, these endpoint results should be interpreted with a careful consideration of the number of cohorts and observations that went into each specific model run.

To estimate changes in persistence over time, we calculated the half-life for each cohort at each site and parameterized a linear model on these half-life values (n = 26 at each site) to identify temporal changes in recultivation patterns at each of our 11 sites (section S2.5). Trends were considered statistically significant when the 95% confidence interval for model coefficients did not include zero (fig. S18).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at https://science.org/doi/10.1126/sciadv.abm8999

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