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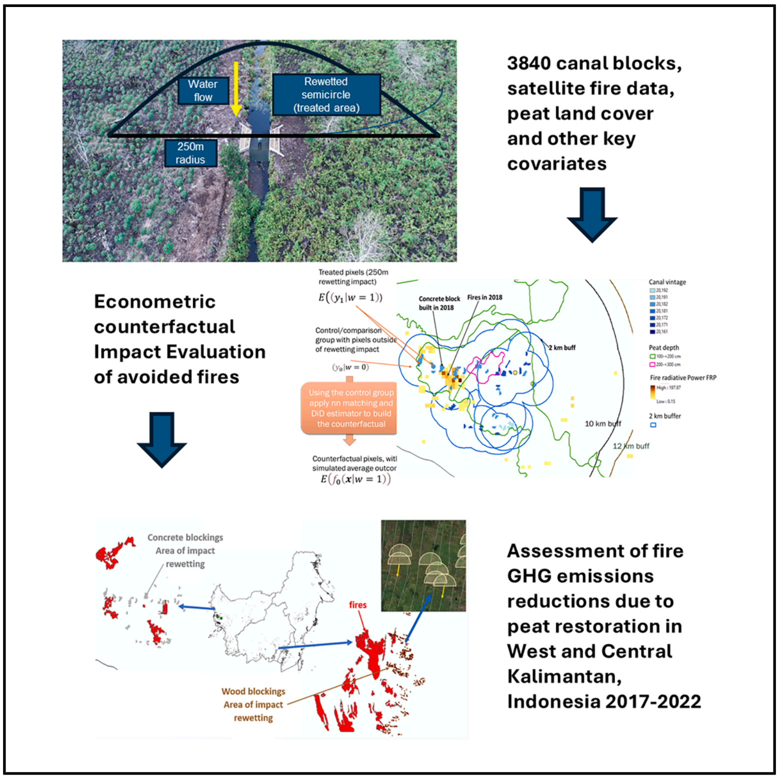
Effective restoration can avoid peatland fires: Large scale counterfactual assessment in Kalimantan, Indonesia

Graphical abstract



Highlights

- We evaluated the impact of 3,840 canal blocks on peat fires in Kalimantan
- Canal blocks with overlapping rewetted areas were the most effective
- Scaling up the best practices could avoid up to 6.4% of the burnt area
- The proposed method can support the robust assessment of GHG emissions reductions

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In brief

Environmental science; Environmental resource; Hydrology; Environmental engineering; Economics; Econometrics

Castro et al., 2026, iScience *29*, 116041
June 19, 2026 © 2026 Published by Elsevier Inc.
https://doi.org/10.1016/j.isci.2026.116041

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Effective restoration can avoid peatland fires: Large scale counterfactual assessment in Kalimantan, Indonesia

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https://doi.org/10.1016/j.isci.2026.116041

SUMMARY

Peatland fires are the third largest source of greenhouse gas (GHG) emissions in Indonesia, a country that stores over half of the world's tropical peatland carbon. These fires cause significant economic losses to human health, crops, and forests. After the devastating 2015 fires, the Government of Indonesia and several partners initiated large scale restoration efforts via peat rewetting with canal blocks. We report on a statistical counterfactual evaluation of peat rewetting on fire occurrence in peatlands in West and Central Kalimantan from 2017 to 2022. We find heterogeneous impacts of rewetting: canal blocks with overlapping rewetted areas were the most effective for avoiding fires. If all canal blocks were effective, rewetting could avoid up to 6.4% of the burnt area, reduce 0.4 MtCO2e emissions, and deliver economic returns of more than a 100% in 10 years in the best performing locations.

INTRODUCTION

Tropical peatlands provide critical ecosystem services, harbor biodiversity, and store immense quantities of carbon. In the past several decades, they have faced degradation and loss primarily through human-driven factors, like deforestation, drainage, and fires for agricultural or other commercial purposes.[1,2] Beyond the loss of stored carbon[3,4] and biodiversity,[5] the degradation and conversion of peatlands can adversely impact human well-being locally and regionally through destructive and intense fires.[6,7] Anthropogenic factors like deforestation and drainage have been largely responsible for transitioning surface and subsurface peatland conditions, which have led to altered water tables, soil moisture deficits, and differential fuel loads that create favorable conditions for fires.[8,9] There is widespread recognition of the importance of effectively restoring tropical peatlands, yet little empirical evidence exists on efforts to date, raising questions about whether current restoration programs are cost effective and whether there needs to be more careful implementation of restoration activities.

Indonesia is a tropical peatland hotspot, storing over half of the world's tropical peatland carbon (57 Gt) with soil carbon stocks per hectare (2,772 tC/ha with an average depth of 5.5 m) six times greater than the average aboveground carbon per hectare in old growth tropical rainforests.[10,11] Indonesian peatlands are also emblematic of the governance challenges associated with juggling broader climate mitigation and resilience commitments with regional economic development goals. Agricultural expansion, primarily a product of land conversion for oil palm and timber plantations, has led to broad-scale deforestation and degradation causing a loss of 21% (1.38 Mha) of the remaining total forest in peatlands area in just ten years 2009–2019.[12,13] Conversion of peatlands often involves lowering the water table via drainage canals, which can increase the risk of peatland fires.[3] Indeed, fire is a primary avenue of regional and global greenhouse gas emissions, as well as impacts on people and nature.

Due to the nature of peatland ecosystems, peatland fires release significantly more emissions compared to fires found in other Indonesian ecosystems.[14] Nearly 70% of total carbon emissions following peatland fires come from the burning of peat soil.[15,16] Although fires in peatlands account for approximately 3% of global carbon lost to fires,[17] the scale and magnitude of peatland fires can lead to disproportionately high carbon emissions. In 2015, the Indonesian peatland fires generated, on average, greater daily emissions (11.3 Tg CO_2) than the European Union (8.9 Tg CO_2).[18] The emissions from fires in peat and non-peat lands also have significant impacts on people. For example, the 2015 fires in Sumatra and Kalimantan are estimated to have resulted in over 100,000 excess deaths in Indonesia, Malaysia, and Singapore,[19] and economic losses are estimated at approximately US$28 billion.[8] Fires can also have adverse impacts on local biodiversity through the destruction of seedbanks and underground perennating organs,[20] loss of canopy cover and habitat,[21] emissions, and river acidification.[22,23]

Recognizing their importance, numerous policies and organizations support peatland conservation and restoration.[8,24] After the devastating fires in 2015, the Government of Indonesia created the Peatland Restoration Agency (Badan Restorasi Gambut, BRG) and committed to restoring 2 Mha of degraded peatlands between 2016 and 2020, ultimately achieving restoration of 834 thousand ha (Yasin pers comm). A new decree in 2020 established the Badan Restorasi Gambut dan Mangrove (BRGM) with a target of 1.2 Mha of peatland restoration from 2021 to 2024.[25,26] Achieving the previously mentioned goals requires investments of approximately US$7 billion.[8,27,28]

BRG's and then BRGM's strategy for peatland restoration involved three core activities called 3R (rewetting, revegetation, and revitalization): rewetting of peatlands to restore water table levels, revegetation of native peat swamp forest species, and the revitalization of peatland community livelihoods.[1] We focused on rewetting for our statistical counterfactual since it was the most implemented restoration practice and the only one with an exact location and extent available in the open web database that we utilized.[29] Rewetting consists of raising the water table to create favorable ecological conditions to revitalize native peatland habitats and reduce the risk of peat fires. There are several proposed methods that have shown varying degrees of efficacy in raising water tables.[30] In Western (WK) and Central Kalimantan (CK), one of the primary methods is canal blocking, which involves constructing dams that are made of lumber or concrete.[31,32] The primary assumption is that effective canal blocking would raise water tables and increase soil moisture, thereby creating conditions that reduce the risk of fires (whether intentional or unintentional).[33] While rewetting tropical peatlands is one factor in reducing fires,[34–36] it also advances ecological goals (i.e., restore peatland habitats for biodiversity and climate change mitigation) and human well-being goals (e.g., reduce the risk of unmitigated fires).

Recent analyses have estimated the potential benefits provided by peatland restoration,[8,37,38] demonstrating that benefits from fire reduction in Indonesia from 2004 to 2015 could have amounted to over US$50 billion in avoided economic losses, over 20% of avoided PM2.5 emissions, and tens of thousands of avoided premature mortalities.[8] Yet estimates of fire reduction benefits from rewetting peatlands are derived from models that use strong assumptions. Results from such models can be useful for providing grounded estimates; however, they may miss critical nuances or diverge widely from real-world estimates because implementing restoration activities can be mired in on-the-ground political, social, economic, logistical, and other confounding factors that limit their efficacy.[28,34,36]

Previous literature has reported on detailed case studies of the impact of rewetting on peat hydrological conditions, especially the water table, in Kalimantan and in other islands of Indonesia.[31,32] Other studies reported that peatland restoration projects in CK did not consider specific reference and trajectory conditions and rather focused on engaging local communities and developing sustainable livelihoods.[39] Research on the challenges, costs, and governance for peatland restoration in CK report qualitative assessments based on key informant interviews that acknowledge the ecological difficulties of canal drained peat that is prone to human-caused fires.[40] Nevertheless, these studies report neither on the quantitative biophysical impacts of peatland rewetting on fires nor perform a large-scale evaluation of all built blocks in Kalimantan.

We fill this gap by developing a large-scale counterfactual evaluation of the actual effectiveness of peat rewetting via 3,840 wood and concrete canal blocks built between 2017 and 2022 on fire occurrence (i.e., whether there was any fire) in peatlands of WK and CK, Indonesia. We use statistical matching and a difference-in-differences (DiD) with multiple time periods model to estimate the impact of canal blocks, a methodology that allows us to leverage a credible counterfactual scenario of what would have happened had canal blocks never been built.[41,42] In short, we employ a well-established method to rigorously estimate the plausible causal impact of rewetting peatlands by comparing similar groups and tracking their change across several years. Our approach accommodates the multiple time periods in which canals were built, accounts for pre-treatment fire trends, and allows us to control for other factors that influence fire risk (see STAR Methods).[43]

We find heterogeneous impacts of rewetting: canal blocks with overlapping rewetted areas were the most effective for avoiding fires. The most effective concrete and wood blocks had the largest proportion of overlapping treatments with up to 5 rewetting semicircles overlapping. The net impact on GHG emissions from all concrete and wood blocks that had a statistically significant effect at a 95% confidence interval, with power at least 80%, is a reduction of 90.55 (±25.18) ktCO_2e emissions for 2017–2022 in both provinces. Projections that assume that the best practices could be replicated in areas with a similar canal network density indicate that canal blocking could have avoided up to 5.8% and 6.6% of the burnt area from 2018 to 2022 in WK and CK, respectively. Notably, the projected effectiveness of scaling canal blocks is less than the value reported in previous cost-benefit studies.[8,44] Even with this lower effectiveness, however, we find that scaling up the most effective blocks could deliver economic returns of up to 225% in CK.

Our results demonstrate the importance of careful empirical investigations that assess the actual effectiveness of peatland restoration interventions, as well as identifying the most impactful interventions for rewetting peatlands. Providing empirical insights regarding canal blocks for peatland restoration can help recalibrate models and cost estimates, demonstrating what interventions should be scaled for ecological and broader societal benefits.[45–47] Our counterfactual approach can support the robust assessment of GHG emissions reductions from fires in peatlands due to restoration, which is particularly important after the ratification of Article 6.4 at COP29 which established standards for a global carbon market.[48,49] Moreover, this research acknowledges the difficulties of restoration, stressing the importance of avoiding further conversion and encroachment of peatland forests.

RESULTS

From 2017 to 2022, BRG and BRGM, with the support of implementing partners, built 3,992 canal blocks in WK and CK.

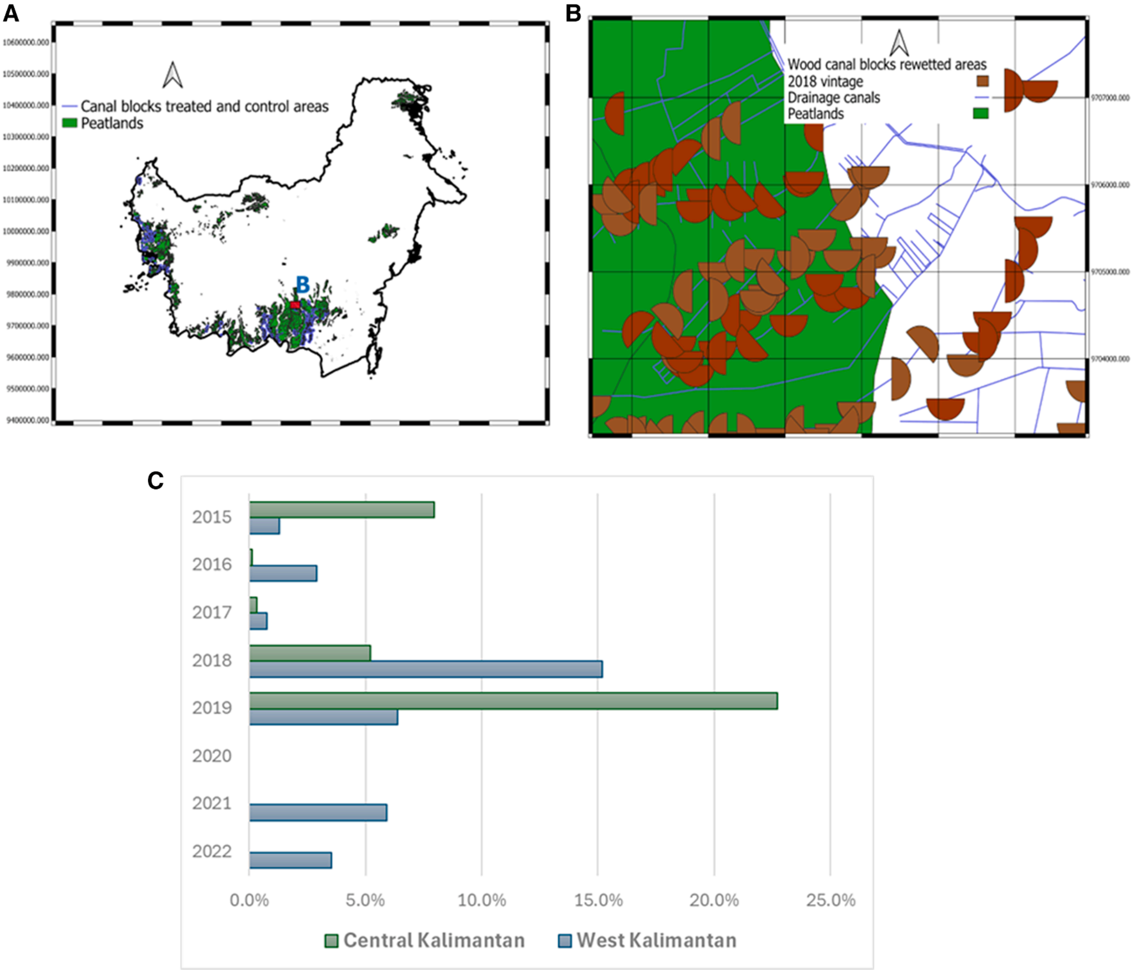

Figure 1. Canal blocks rewetted areas and fire occurrence

(A) The general location of the study areas and peatlands in Kalimantan (further details on Figures S3 and S4).

(B) A zoom into a specific location in Central Kalimantan to showcase the overlapping rewetted areas (see STAR Methods).

(C) The fire occurrence (%) by province and year in the study areas. The fire occurrence is for all rewetted or treated areas (250 m semicircles) and control buffers (2 km) in both provinces (see STAR Methods).

Our database captures 3,840 blocks (96.2%). We use a 250 m radius semicircle of impact (treatment) upstream of the waterflow and estimate that these canal blocks rewetted 6,280 and 16,477 ha of peatlands in WK and CK, respectively (STAR Methods). Our data show that in WK, 200 wood blocks were built in 2017 and 638 concrete blocks were built between 2018 and 2022. In CK, 3,002 wood blocks were constructed from 2017 to 2022. Total rewetted area by wood and concrete blocks is 18,162.5 and 5,664.8 ha, respectively (Tables S1 and S2; Figures S1–S3). In regions with a large canal network density, blocks can be located close to each other resulting in overlapping rewetted areas, which account for 25.5% of the total 23,827.3 ha rewetted (treatment areas with at least one overlap, Figure 1 STAR Methods; Table S3). Based on the MODIS burned area fire satellite data, there were 1,700 and 4,627 ha of peatland burnt during 2017–2022 inside all rewetted areas in WK and CK, respectively (see STAR Methods and Table S90).

Fire occurrence in our study areas vary by province and year. For the rewetted and control areas in CK, the dry El Niño years of 2015 and 2019 had the largest fire occurrences, and there were no fires from 2020 to 2022. On the other hand, WK had the worst fire year in 2018, followed by 2019 and then 2021. WK had fires in the study areas all years except for 2020 (Figure 1; Table S4). The restoration areas in WK had fires during more years than the restoration areas in CK, likely since the treated peatlands are on average 7 times closer to agricultural lands in WK than in CK (Table S5). Being closer to agricultural lands put restored peatlands more at risk of spillover of fires, which were usually started for clearing the fields or reducing weeds and pests.[50] However, in total for all years in the period 2015–2022, both provinces had almost the same total level of fire occurrence: 4.5% for both WK and CK. While fires were more constant throughout the years in WK, they were more widespread in the dry years in CK, especially in 2019, which could be due to drier peat facilitating the spread of flames.

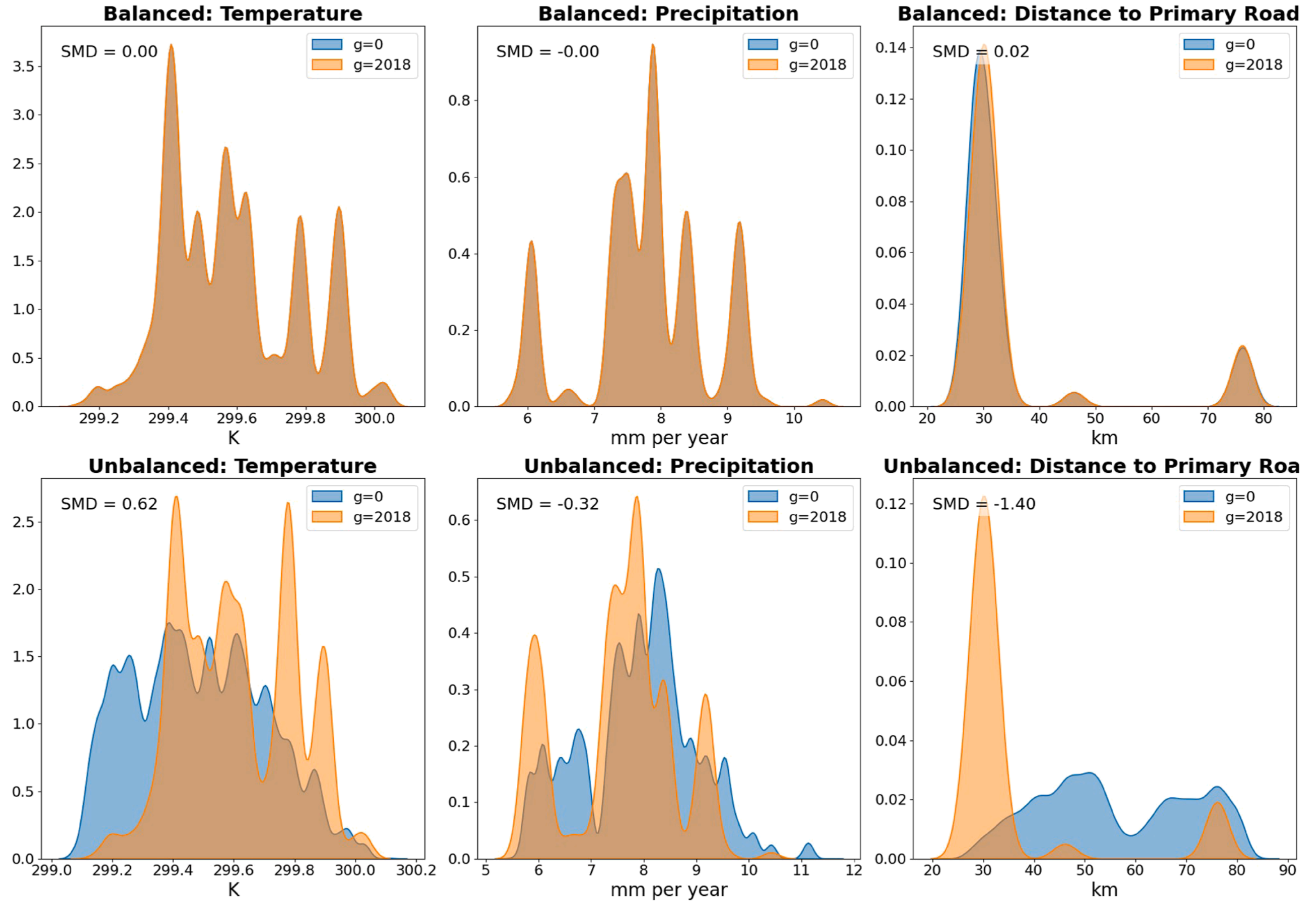

Figure 2. Distribution densities of variables that influence fires before (unbalanced) and after (balanced) selecting (matching) the most similar comparison areas (controls) for locations rewetted by canal blocks built in 2018 (treated) in the kecamatan 6203010

SMD stands for standardized mean difference and g represents treatment status. If g = 0 it means untreated or control units and if g = 2018 it represents treated areas with canal blocks built in 2018. Figures S5–S13 show detailed results for the other variables in all other kecamatan evaluated.

While there is variation in fire occurrence by year and province due to different underlying conditions, we control for all those factors by finding the best areas for comparison (controls) in the same locality (kecamatan) for each year. The next section explains and presents the results of this in more detail.

Controlling for other factors that influence fires

We controlled for the influence of other factors on fires, such as climate, terrain, socioeconomic (distance to roads, land use, and population density), fire occurrence in 2015 and in the two years before the block construction, and the time and spatial lags of fires, by finding the most similar units for comparison with statistical matching and then further isolating the impact of just the canal blocks with the multiple period DiD regressions (STAR Methods). Hence, matching allowed us to balance the other variables that affect fires aside from canal blocks in treated and control units obtaining standardized mean differences below the conventional threshold of 0.2 (Figure 2; Figures S5–S13).

Matching also yielded balanced initial conditions regarding the fires in the two years before the construction of canal blocks (i.e., treatment implementation) and the fires of the El Niño year 2015 (Figure 3). Thus, our method was able to find the best comparison units to isolate the causal impact of rewetting by comparing areas with similar initial conditions. Moreover, we also performed the conditional parallel trend test of DiD on the balanced data for each kecamatan evaluated to further assess that treatment and controls did not differ significantly in fire occurrence before restoration. For those kecamatan that did not pass the conditional parallel trend test, we do not consider their results to be significant since no valid statistical counterfactual inference is possible (see STAR Methods and Table S6).

Using the balanced data from matching, we evaluated the causal impact of canal blocks, separating it from the influence of other confounders via multiple period DiD estimators.[43] Having individual models for each kecamatan provides flexibility in assessing how different factors that influence fires vary by region. Hence, variables such as temperature had a positive statistically significant influence on the probability of fire occurrence in certain kecamatan, while in others it did not play a significant role, but rather other factors such as distance to agriculture or forests played a determining role (Figure 4; Table S7). The DiD estimator calibrates different fire probability equations for each

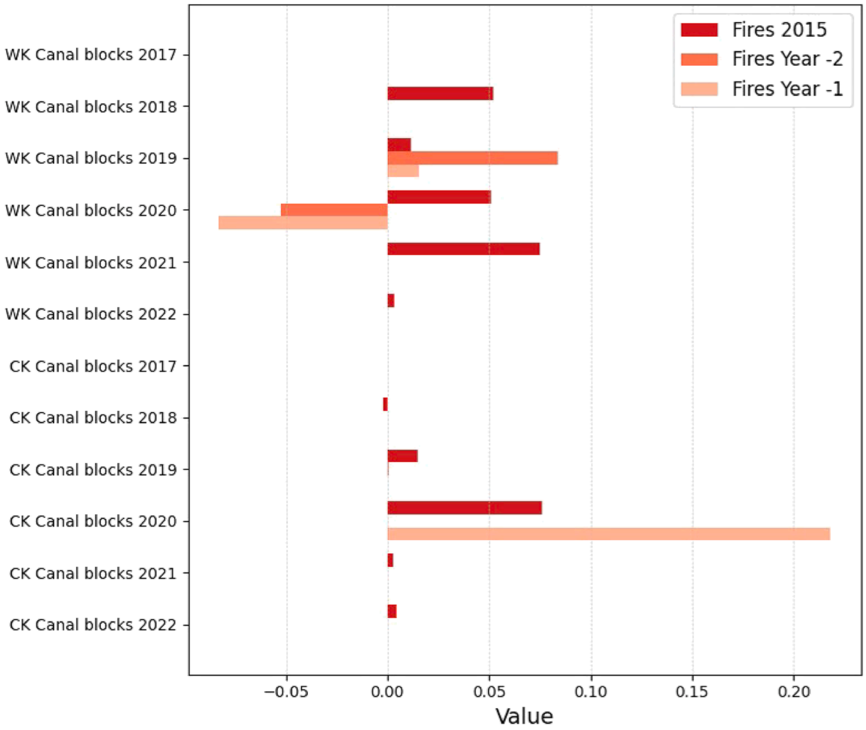

Figure 3. Standardized mean difference of fires before restoration between treated and control areas in all kecamatan for all canal blocks

year allowing us to model fires during very dry years (2019 EL Niño) differently from fires during other years. To summarize, we were able to control for the influence of other factors on fires to have a valid inference of the impact of rewetting on fires.[46]

Overlapping rewetted areas are the most effective for avoiding fires

We found heterogeneous and statistically significant impacts related to avoided fires from canal blocks when we build counterfactuals by kecamatan, year of construction, canal block type (wood or concrete), and rewetted area type (treated areas with or without overlaps) (see STAR Methods). We present the causal estimates (average treatment effect on the treated, or ATT) of rewetting via canal blocks on fire occurrence. We show and discuss the results for the treated areas that were both statistically significant at a 95% confidence interval and with a statistical power of 80%, which we found out to be 4% and 25.6% of all treated areas in WK and CK, respectively (see STAR Methods). All the other results that are not statistically significant are presented in the SI (Tables S8–S88).

Total avoided fires by overlapping and simple rewetted areas in both provinces for 2017–2022 were 174.7 ha representing 2.8% of all burnings inside treated areas (as defined by the 250 m semicircles). Overall, CK had a larger number of effective canal blocks that avoided, in aggregate, 3.2% of all fires inside rewetted areas in the province, while in WK all effective blocks avoided 1.7% (Table S90). In CK, we found the majority of kecamatan with overlapping rewetted areas that avoided fires in 2018 and even in the dry El Niño year of 2019. However, in other kecamatan, blocks caused an increase in fires in 2019 yielding a not statistically significant net impact that year. The net total impact of peat rewetting with canal blocks for all years (2017–2022) in CK is a reduction of fires in 145.8 ha ($p = 0.000$). In WK, concrete blocks built in 2018 that generated overlapping rewetted areas avoided fires during 2021 and 2022 with a net total impact of 28.9 ha of avoided fires ($p = 0.000$) (Figure 5; Table S89). Fires could not be avoided in the year of highest occurrence (2018) in WK (Figures 1 and 5).

Overlapping rewetted areas are the most effective; they are responsible for 70% of total avoided fires in the study area from 2017 to 2022 (121.6 ha total with 92.7 ha in CK and 28.9 ha in WK). The effective blocks that caused an overlap avoided 7.9% and 15.2% of all fires inside overlapping rewetted areas in WK and CK, respectively. During the study period fire occurrence in overlapping rewetted areas was 4.8% and 6.4% in CK and WK, respectively (Figure 1; Table S97). Effective overlapping restoration prevented 0.6% and 0.9% of the total overlapped restored area from catching fire in WK during 2021 and 2022, and 7.5% of the overlapped restored area from burning in CK in 2018 (Table S97). The most effective blocks, which avoided fires for two years and contributed the greatest area of reduced burns, were wooden blocks located in CK that had overlapping rewetted locations. On relative terms, these blocks reduced fire occurrence in 11.4% and 5% in the overlapping rewetted areas during 2018 and 2019, respectively (Figure 6). In WK, we found the most effective canal blocks on relative terms for a given year: concrete blocks that generated overlapping rewetted locations that avoided fires on 15.6% of the total treated area (Figure 7).

The most effective blocks in each province had the largest share of overlapping treatment areas with respect to total rewetted surface in the kecamatan. This overlap or multiple dosing of the treatment (defined by the 250 m semicircles) was facilitated by having a very dense canal network which allowed having blocks constructed close to each other leading to more inundation in overlapped surfaces (Figure 7, STAR Methods; Table S91). Those effective blocks in kecamatan 6103100 and 6203010 avoided fires in spite of burning dynamics strongly linked to agriculture and mining since nearness to agricultural and mining lands, as well as to secondary forests that were burnt to facilitate agriculture, increase the probability of fire occurrence in those locations (Figure 7; Table S7). Moreover, the most effective blocks had not only the largest proportion of overlapping treatments with at least two semicircles intersecting, but they also had the largest areas with several treatment

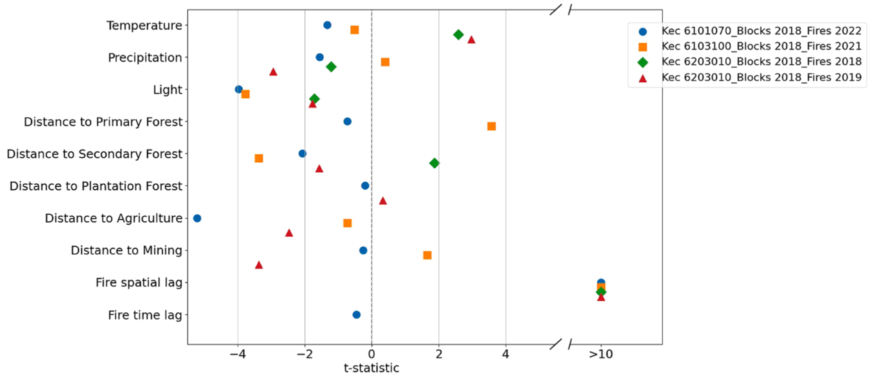

Figure 4. Influence and significance of factors on the probability of fire occurrence

Kec stands for kecamatan. Results are displayed for a sample of kecamatan of interest where canal blocks had a statistically significant impact of on fires. More detailed information is displayed on Table S7.

semicircles crossing each other. Hence, the most effective wood blocks had up to 5 rewetting semicircles overlapping and almost a quarter (24.4%) of the overlapping surface had 3 or more intersecting semicircles. For the most effective concrete blocks, 21.6% of the overlapping area had 3 or more intersecting treatment areas and up to 4 overlapping treatment semicircles (Table S92).

The number of blocks per unit of rewetted area is 0.067 and 0.068 per ha in both best-performing locations in WK (concrete) and CK (wood blocks), respectively, and the average distance to the nearest canal block in those effective locations is 162.4 m for WK and 195.3 m for CK (Table S98). The key issue for an effective restoration design, based on our findings, is to place blocks in the same canal line within that distance but also to place other blocks within that distance in other nearby canals to achieve overlapped inundation within a 250 m radius. Based on field observations by the co-authors, canal size, water flow, and elevation also contribute to this effect and the designation of 250 m as a significant radius.

In all, except one, kecamatan that had at least one statistically significant result, the blocks with overlapping rewetted areas performed better than their non-overlapping counterparts. The exception is kecamatan 6203140, where the rewetted area with overlaps had a significant increase in fire occurrence 2019, since the overlapping rewetted area only represented 7.6% of the total treated surface and it only had up to 2 rewetting semicircles overlapping (Figure 7). Hence, the low level of multiple dosing in that kecamatan and very likely other unobserved factors in our study, such as damaged blocks due to navigation of boats through the canals or soil compaction affecting the wood blocks, caused an increase in fires. Kecamatan 6203080 is the other one where the wood blocks with no overlapping rewetted areas led to a fire increase.

Concrete and wood blocks reduced GHG emissions

The net impact on GHG emissions from all concrete and wood blocks that had a statistically significant effect at a 95% confidence interval, with power at least 80%, is a reduction of 90.55 (± 25.18) ktCO_2e emissions for 2017–2022 in both provinces (p = 0.0001, Figure 8). This value is a conservative estimate since it accounts for the impact of all years excluding the not significant (at 95% confidence interval [CI]) net emissions reductions of 2019 where certain blocks led to fire increases (Figure 8 and previous sections). It's worth stressing that the assessed GHG reductions are only attributed to canal blocks avoiding fires since our statistical impact evaluation method controlled for the climate conditions specific to each year as developed in the subsection "Controlling for other factors that influence fire".

Scaling up effective canal blocks can avoid fires in peatland cover and reduce GHG emissions

Our aforementioned results report on the plausibly causal estimates of peatland rewetting via canal blocks on fire occurrence, finding that not all blocks were effective. But what would the reduced emissions benefits be had the most effective canal blocks been placed where feasible? We projected the benefits of canal blocking on fire occurrence and emissions assuming that the best practices could have been replicated in areas with a similar canal network density (STAR Methods). We find that, on average, up to 6.4% of the burnt area (381 ha) from 2018 to 2022 could have been avoided in both provinces: 5.3% (808.3 ha) in WK and 6.6% (338.4 ha) in CK, respectively (Table S93). Scaling up both types of effective blocks that had overlapping rewetted areas could have avoided fires and GHG emissions would have been reduced, on average, by 197.5 ktCO_2e: 22.1 and 175.4 ktCO_2e in the study area of WK and CK, respectively (STAR Methods and Table S93). For the estimated life cycle of the infrastructure, 10-year time horizon, scaling up the best practices could deliver emissions reductions of 0.4 MtCO_2e in the projected best performing locations (Table S94).

DISCUSSION

Our results highlight the importance of careful and high-quality implementation of canal blocks to reduce fires in peatlands. Canal blocks that properly raise the water table, either by being located close to each other leading to overlapping rewetted areas or by having a solid standalone design that causes areas to be inundated, reduce fire occurrence on peatlands. The finding of a higher effectiveness in overlapping rewetted areas is in line with previous literature.[51] In total, our counterfactual analysis indicates that the causal impact of both concrete and wood canal blocks led to 90.55 (±25.18) ktCO2e of avoided emissions during 2017–2022 (Table S90).

Our analysis of total avoided emissions from scaling up the most effective blocks found 197.5 ktCO2e of GHG emissions reductions could have been achieved between 2018 and 2022, reducing burnt area in WK and CK by 6.4%. This result is a

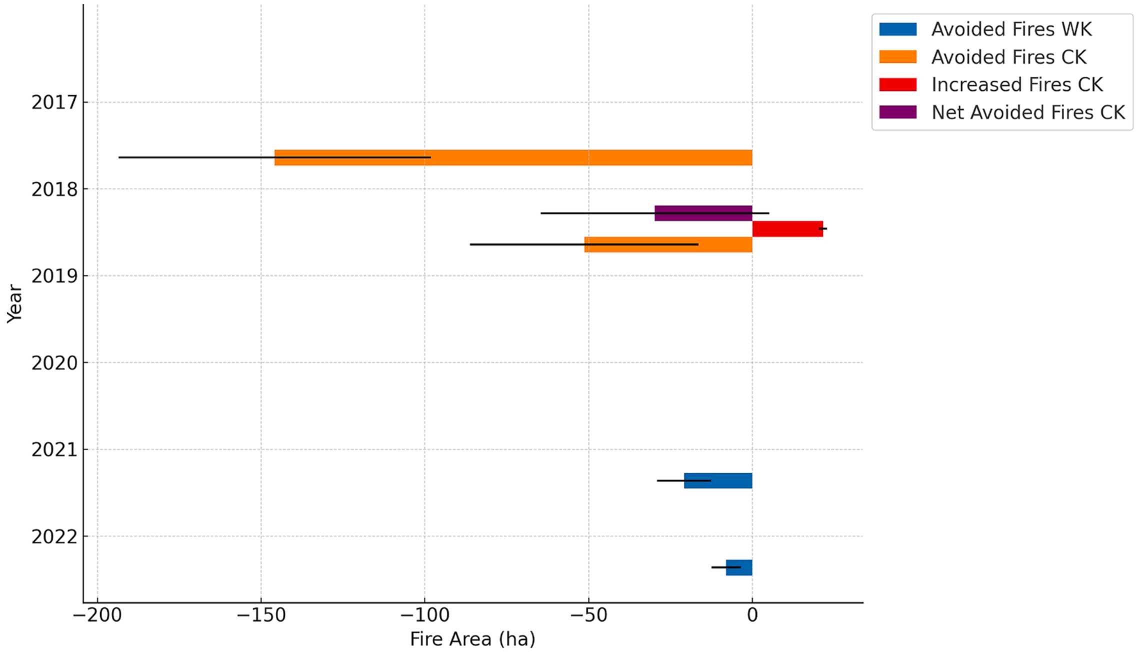

Figure 5. Impact on fire area from all canal blocks that had a statistically significant signal 2017–2022
CK and WK stands for Central and West Kalimantan, respectively. The error lines represent the 95% CI. All statistically significant results (simple and overlapping rewetted areas) are included in the annual aggregates displayed.

more conservative estimate than those in the previous literature. For example, cost-benefit assessments assumed a 37% reduction,[8] and restoration prioritization studies have modeled 40%[44] and 17%[28] decreases in burnt area from peatland rewetting.

The fire-related GHG emissions reductions coming from the canal blocks could have financed 9.2% and 30.6% of the construction cost in the kecamatan with effective blocks in WK and CK, respectively (Table S95). If best practices were implemented in areas with a similar canal network density, the fire-related GHG offsets alone would generate economic returns of 5.4% and 225% for a 10-year horizon in WK and CK, respectively (see STAR Methods and Table S96). Accounting for the value of all emissions reductions resulting from reduced soil oxidation after rewetting strengthens the case for the financial and economic feasibility of this type of restoration.[52]

While the impact we found of the best canal blocks with overlapping rewetted areas is conservative, it is very likely that improved practices could achieve better results and prevent more fires. Since the best performing blocks in one year were concrete blocks in WK with 38.3% of overlapping rewetted areas having up to 4 intersecting semicircles and reducing 15.6% of fires (Figure 7; Tables S91 and S92), having concrete blocks in the dense canal networks of CK, with four or five overlapping treatment areas, could hypothetically be a cost-effective option to significantly curtail fires and reduce GHG emissions. This is a design option worth exploring and evaluating for policy makers and restoration practitioners.

We find heterogeneous impacts of both concrete and wood canal blocks on fire occurrence. Our econometric method relies on robust counterfactuals for each province, year of construction, canal block type, and rewetted area type, which provides enough statistical power to allow investigation of impacts at a detailed level (STAR Methods). The heterogeneity in impacts indicates that there are several factors that dictate why some canal blocks are more effective than others. While we do not have sufficient data to explore all factors, such as the quality of canal block construction or whether the blocks were damaged by boats, we examined some hypotheses for heterogeneous impacts, finding that the amount of rewetting overlap is the key factor for avoiding fires in kecamatan with different fire socioeconomic drivers.

Canal blocks are one method for reducing peatland fires; these efforts should be complemented with outreach campaigns that aim to change behavior related to agriculture and fire to ensure effective reduction in fires. Continuous monitoring and evaluation of future deployment of canal blocks will be critical for identifying best practices for scaling up an effective peatland rewetting program.

A number of robustness checks and alternative assumptions validate our results. Using areas located further away from the semicircle (2–4 km buffer) as controls does not provide statistically valid comparisons, which supports our research design and results (STAR Methods and Figure S14). Variation in canal block implementation could be a threat to validity; however, documentation by BRG (named later BRGM) indicates that design, construction procedures, and cost of infrastructure were similar for both agencies.[53]

Our study is the first to provide empirical evidence for the efficacy of canal block rewetting on reducing fires in peatlands using a counterfactual framework. Failing to account for systematic

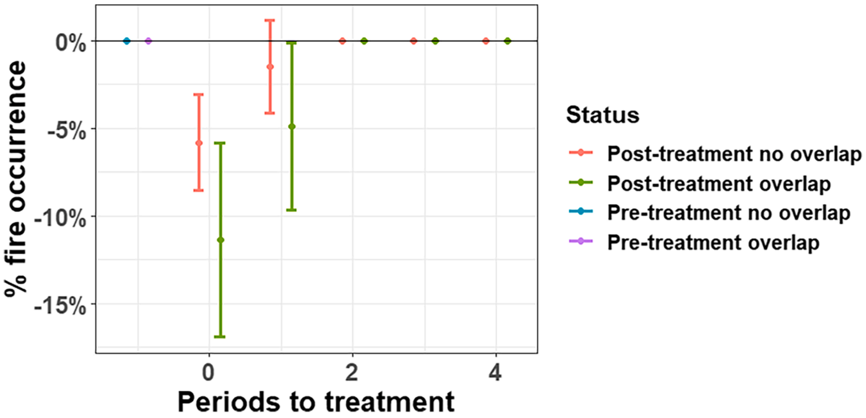

Figure 6. Impact on fire occurrence in kecamatan with the most effective canal blocks built in 2018

Estimates at zero are due to having no fires in the treatment nor in the control areas during those years. The kecamatan has the code 6203010 and is located in Central Kalimantan. Details on Tables S49 and S50.

differences between areas with canal blocks and areas without canal blocks would have led to false inferences. A simple comparison of fire occurrence rates between rewetted and control areas would mistakenly lead to the conclusion that wood blocks produced a 17.5% increase in the burnt area (809 ha) proximate to the canal block. Likewise, simply comparing fire occurrence between rewetted and control locations would lead to incorrectly inferring a 61.2% increase in fires (1,040 ha) in WK due to canal blocks. These incorrect inferences demonstrate the importance of adjusting causal estimates from canal blocks using counterfactual comparisons (results and STAR Methods).

Our approach builds on established methods for estimating causal impacts using a quasi-experimental framework and addresses limitations of past studies that have relied instead on machine learning prediction that lacked a counterfactual.[44] Statistical counterfactual methods have been used to robustly assess treatment effects in medicine and social sciences, yet they are rarely used for assessing natural climate solutions and the associated co-benefits provided by conservation actions.[47,49,54] In fact, carbon markets standards are currently incorporating these counterfactual or dynamic baselines methodologies for removals and assessing emissions reductions.[55] Our proposed counterfactual method can support the robust assessment of GHG emissions reductions from peat fires due to restoration which is a key pending task for voluntary carbon markets and other new climate finance instruments.

Tropical peatlands, and especially those in Indonesia, store globally significant amounts of carbon. There are local and global imperatives to reduce peatland fires, which can create harmful smoke locally and regionally, and release significant GHG emissions, especially during large-scale fire events. Recent increases in wildfires in other regions with major peat deposits in the tropics underscore the local and global significance of peatland rewetting via canal blocks to reduce peatland fires; for example, the Pastaza-Marañón Basin in the Western Amazon recently experienced significant fires.[56,57] Our insights on the difficulties of restoration and the importance of avoiding further conversion should be a cautionary tale for the conservation of those landscapes. For areas already converted, our methods and insights offer guidance on how to assess the effectiveness of peat restoration on reducing fires.

Our results demonstrate the challenges of effective restoration. Fire-related benefits from canal blocks in Indonesia have been overestimated, but they nonetheless reduce fire occurrence and provide economic returns after accounting for the full social cost of climate change mitigation. Importantly, restoration activities should continue to complement peatland protection and improved management.[45,58] Avoiding further degradation, fragmentation, and fires will require concerted and careful efforts to realize climate, human health, and biodiversity benefits.

Limitations of the study

Our study represents an empirical advance on the impacts of peatland restoration on fire occurrence. With improved data, future studies could distinguish between surface peatland fires and fires that turned into underground peat fires, which are an important but hard to detect source of emissions. The satellite fire data tells us that burnings occurred in a given pixel or area with peat soils[59] but separating between surface and underground peat fires is beyond the scope of this article. Therefore, when we refer to peatland fires, we mean satellite-detected fires on lands that have peat soils.[60] Further, future studies should incorporate more contextual data to improve the precision of estimates. Data on transportation infrastructure, local water tables, and soil quality are likely important correlates. Indeed, our study presents recent and robust evidence, but we are unable to assess certain drivers of fire occurrence or canal effectiveness due to data limitations. For example, the use of certain canals for boat transportation could have led to canal block damage in ways that we cannot observe and control for in the counterfactual analysis. Ideally, having detailed spatial information on the water table for the entire study area could further strengthen the proposed statistical counterfactual and help to understand the underlying hydrological process and its influence on fire occurrence.[32] Unfortunately, such detailed data are not currently available for all 3,840 evaluated blocks in order to use them as one of the spatial layers.

While there is no publicly available updated information on the state of all canal blocks, even if some infrastructure was damaged and destroyed, our estimates would, in the worst-case scenario, be conservatively downward biased. If canal blocks were damaged or destroyed, our estimates would find canal blocks caused an increase in fires, thus leading to underestimating the fire reductions from all combined canal blocks in peatlands. In fact, damaged canal blocks could explain the increase in fires that we find in two kecamatan (Figure 7). Even with

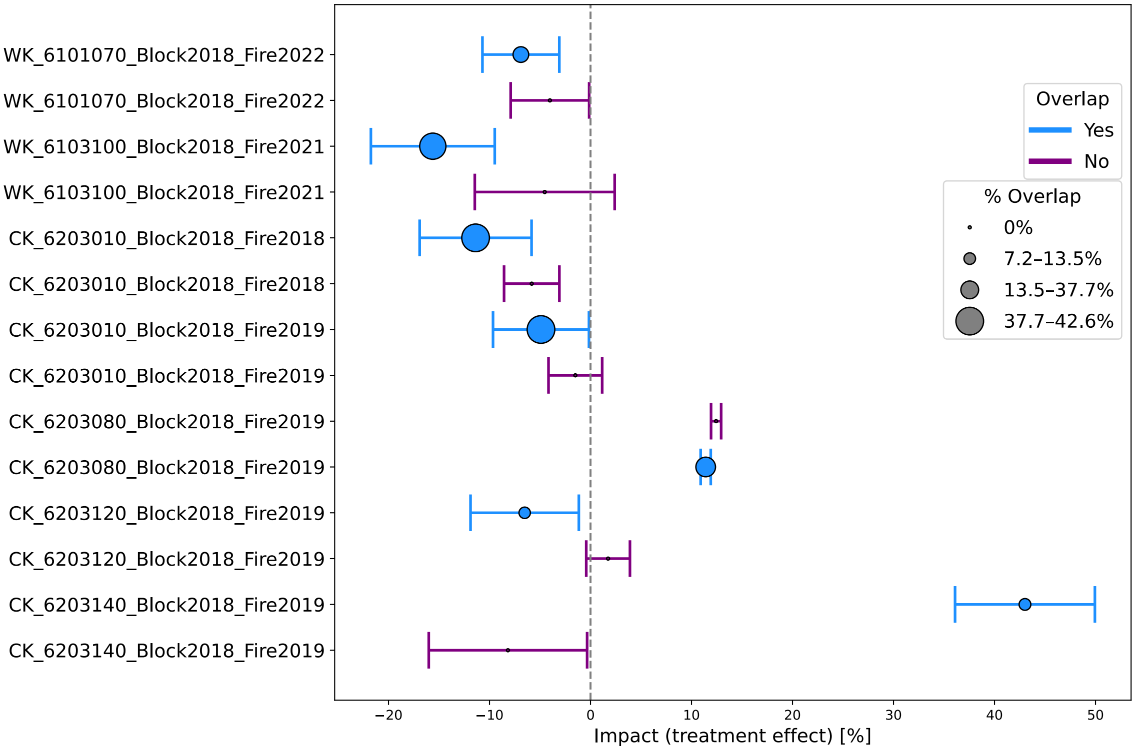

Figure 7. Impact of canal block rewetting on fire occurrence (%) in all effective areas (simple and overlapping rewetted)

CK stands for Central Kalimantan (only wood blocks) and WK for West Kalimantan (only concrete blocks). B stands for blocks and F for fires. All pairs of simple and overlapping rewetted areas in each kecamatan with at least one statistically significant result are presented to compare their effectiveness. The number code is the kecamatan administrative division code. The impact coefficient in kec 6203080 for the blocks that have overlap is statistically significant at a 95% CI but the statistical power is less than 80% so it is shown for illustration purpose. Results for all other years and kecamatan are displayed on Tables S8–S88.

imperfect information, our counterfactual assessment was able to show aggregate net GHG reductions related to fires after peatland restoration in the study area.

RESOURCE AVAILABILITY

Lead contact

Further information should be directed to and will be fulfilled by the lead contact, Miguel Castro (miguel.castro@tnc.org).

Materials availability

No new materials were generated in this research.

Data and code availability

- The data used in this paper is available in the sources reported in the key resources table of the STAR Methods.
- This paper does not report original code.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

ACKNOWLEDGMENTS

We thank Agus Yasin from BRGM and Susan Cook-Patton from The Nature Conservancy (TNC) for their very helpful and insightful comments that improved the manuscript. We also thank participants at the European Geosciences Union EGU General Assembly 2023 Tropical peatlands: Past, Present, Uncertain Future session for their ideas and feedback. Funding support for this research was provided by the Bezos Earth Fund, TNC's FinishLine Fund, and the Sall Family Foundation. Ideas expressed do not necessarily reflect the views of the Bezos Earth Fund, the Sall Family Foundation, or TNC and its affiliates.

AUTHOR CONTRIBUTIONS

Conceptualization, M.C., Y.M., and J.E.; methodology, M.C., R.R., and N.N.; investigation, M.C., R.R., Y.M., A.A., N.N., and A.G.; data curation M.C., G.C., and S.Y; formal analysis, M.C. and R.R.; writing – original draft, M.C., Y.M., R.R., A.A., A.G., and J.E.; editing, M.C., Y.M., J.E. and S.L.; visualization, M.C, Y.M., and R.R.; funding acquisition, S.L.

DECLARATION OF INTERESTS

The authors declare no competing interests.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- METHOD DETAILS
  - Fire satellite dataset
  - Processing the spatial covariates to control for other factors influencing fire risk beyond rewetting
- QUANTIFICATION AND STATISTICAL ANALYSIS
  - Matching and balancing the dataset for the DiD counterfactual assessment

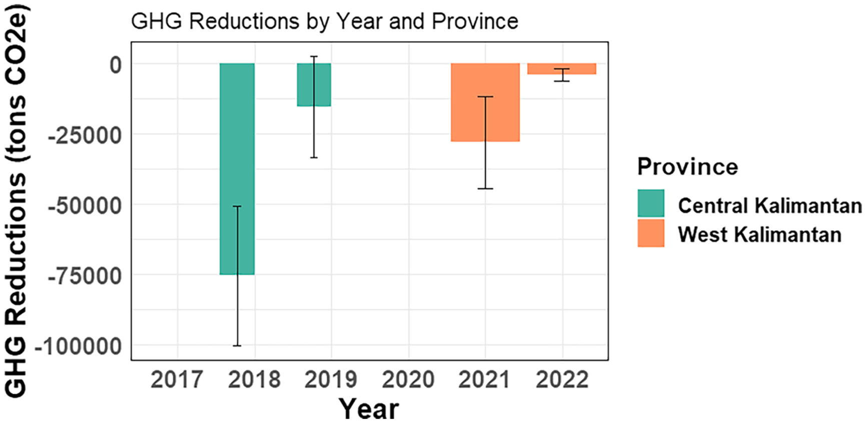

Figure 8. Impacts of canal blocks on GHG emissions (tCO$_2$e)

The GHG emissions reductions due to avoiding fires of the 2018 concrete blocks in 3 southern subdistricts of West Kalimantan, where the *x* axis shows the year of fire. Results for all other years are in the supplemental information. The error bars and band display the 95 percent confidence interval. All results are presented in the supplemental information (Figures S8–S22).

- Identification of the causal effect of canal blocks on avoiding peat fires
- Robustness checks
- Calculating the avoided fire areas
- Projecting the scale up of best practices
- Reduced GHG fire emissions
- Assessment of costs and benefits of reduced GHG fire emissions

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2026.116041.

Received: March 27, 2025
Revised: November 15, 2025
Accepted: May 5, 2026

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
MCD64A1.061 MODIS Burned Area Monthly Global 500m	Google Earth Engine Data Catalog	https://developers.google.com/earth-engine/datasets/catalog/MODIS_061_MCD64A1
Peatland rewetting canal blocks	Web dashboard of BRGM containing the location, year of construction and material type of canal blocks.	PRIMS[29]
Land cover 2015–2019 Ministry of Environment and Forestry (MoEF) national dataset.	Indonesia Ministry of Forestry	https://geoportal.menlhk.go.id/portal/apps/webappviewer/index.html?id=2ee8bdda1d714899955fccbe7fdf8468
Peatland location and depth map	Anda et al.[60]	https://www.sciencedirect.com/science/article/abs/pii/S0016706121003153
Digital elevation model data	Earth Data NASA	https://www.earthdata.nasa.gov/sensors/srtm
Roads	Globio	https://www.globio.info/download-grip-dataset,
Indonesian administrative units	Data.World	https://data.world/ocha-roap/84a1d98a-790b-4d66-9d14-bbfa48500802
Indonesia oil palm concessions	Global Forest Watch	https://data.globalforestwatch.org/datasets/f82b539b9b2f495e853670ddc3f0ce68_2/explore
Temperature_2m and total_precipitation data	Google Earth Engine Data Catalog	https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_LAND_MONTHLY_AGGR
Intensity of night lights	Google Earth Engine Data Catalog	https://developers.google.com/earth-engine/datasets/catalog/NOAA_VIIRS_DNB_MONTHLY_V1_VCMCFG#description
Software and algorithms		
R statistical platform. Version 4.3.2	R Core Team	https://www.r-project.org/
Stata 17	StataCorp LLC	https://www.stata.com
ArcGIS Pro 3.2	ESRI	https://pro.arcgis.com/en/pro-app/latest/get-started/download-arcgis-pro.htm
Csdid: Difference-in-Differences with Multiple Time Periods in Stata	Rios-Avila et al.[61]	https://www.stata.com/meeting/us21/slides/US21_SantAnna.pdf
MatchIt: Nonparametric Preprocessing for Parametric Causal Inference. Version 4.5.5.	Ho et al.[62]	https://CRAN.R-project.org/package=MatchIt
ArcGIS API for Python	ESRI	https://developers.arcgis.com/python/latest/guide/overview-of-the-arcgis-api-for-python/

METHOD DETAILS

Fire satellite dataset

For fire occurrence from 2015 to 2022 we used the MCD64A1.061 MODIS Burned Area Monthly Global 500 m.[63] This data product had the best performance for detecting fires in peat land cover in Indonesia with overall accuracies ranging between 0.48 and 0.58.[64] Moreover, it quantifies the uncertainty (0–100) of fire occurrence for each pixel/area, providing detailed information on where fires likely happened throughout our study period. We filtered the data for using fires only with an uncertainty $\leq$10%; and then processed the raster (using the *raster* package in R) to align with the treated areas raster with a resolution of 50 m.

Description of the procedure for defining the treatment (rewetted) and control areas

The canal block shapefiles were manually digitized based on available coordinates from the national peatland restoration dashboard.[29] Firstly, we filtered restoration types by including only the construction type known as '*Implementasi Restorasi Konstruksi*' or SISFO, which contained canal block point shapefiles. After selecting a specific point, we documented information including coordinates, administration boundary (village-province), year of construction, and the type of construction (whether it is wood or concrete). As a result, we have a detailed database for actual canal blocks implemented from 2017 to 2022 to further define their rewetting impact areas.

We assess the reduction in fire occurrence in rewetted peatland areas with wood and concrete canal blockings (treatment) with respect to untreated or control areas based on the blockings built between 2017 and 2022 in West and CK.[29] We define the treated areas as the 250 m radius semicircles upstream of the blocked canal (opposite direction of the flow) and the control areas as the remaining area within a 2 km circular buffer of the block. For the control areas we used the buffer tool of ArcGIS pro to create circular buffers around all canal blocks and for the treatment areas we implemented the procedure described in the following lines.

We used the canal block point shapefiles derived from BRGM to assess the area affected by rewetting activities. The area subject to rewetting by the canal block is indicated with a semicircle in the opposite direction to the flow direction (contrariwise direction) with radius of 250 m. We perform our counterfactual analysis using a 250 m radius based on the findings of Sutikno et al.[65] who showed that canal blocks could raise the water table in the peatlands at a radius of 170 m, Evans et al.[66] who found that subsidence of drained Acacia plantations extended 300 m into adjacent forest, and Sutikno et al.[67] who argue that canal blocks rewetting extends for 201 m perpendicular to the canal when the raise in the water table is more than 0.6 m. To create semi-circle shapefiles, the canal block points were used as the basis raw data to transform point to semi-circle polygons. The point shapefiles contained information of type of construction (woods or concrete), year of construction (2017–2022), village location, and coordinate. As we found several canal blocks were not located along the canal line from the BRGM dataset, we filtered the data by excluding all canal blocks that had a distance >5 m from canal lines using the "Near" tool of ArcGIS Pro v1.2.

By only selecting filtered shapefiles, we calculate the rewetting impacted area using multiple algorithms of ArcGIS API for Python with PyCharm IDE. To create contrariwise semi-circle shapefiles, the canal blocks were buffered with radius 250 m, hence each semi-circle shapefile will have size 9.8 ha. The SRTM-DEM with resolution 30 m was used to produce flow direction raster of canal lines by considering D8 flow method.[68] With the direction code derived from D8, the buffered canal blocks were contrariwise sliced from the direction of the canal. Despite not being fully perpendicular to the canal line, due to limited direction from D8, the semi-circle was assumed to be correctly directed to the actual canal line for this analysis (Figure S14).

Using the shapefiles of the semicircles of rewetted areas for each canal block vintage, created with the procedure described above, we rasterized them at a resolution of 50 m for creating the numeric database for the statistical model and proceeded to identify overlapping rewetted areas with at least two semicircles intersecting (procedure implemented in R with the *raster* package). Hence, we were able to create separate counterfactual statistical models for the simple or no overlap and for the overlapping (any number of intersecting semicircles) rewetted areas (more details in sections below).

Processing the spatial covariates to control for other factors influencing fire risk beyond rewetting

Our study utilized climate, land use types, road networks, and topography factors to obtain the covariates that determine fire occurrence and intensity. We obtained temperature at 2 m above the surface and total precipitation data from the European Environmental Agency ERA5 monthly aggregated climate reanalysis data.[69] We obtained the annual averages of the climate variables for each pixel in the study area during the period 2015–2022. We proxied population density using the satellite data on intensity of night lights for the study period and using the average annual values for each pixel.[70]

Land cover 2015–2019 was derived from the Indonesian Ministry of Environment and Forestry (MoEF) national dataset. This dataset comprises of 23 land cover types in Indonesia that is updated annually by manual delineation and ground truthing (see SI). As peat fires are connected to unique low elevation and gentle slopes, we also processed the rasters of a digital elevation model to extract altitude and the slope angle derived from Shuttle Radar Topography Mission (SRTM) with a spatial resolution of 30 m-pixel or 1 arc second of latitude and longitude product.[71] We collected road network data from the Global Roads Inventory Project database (GRIP, 2024), the peatland map for Indonesia from Anda et al.,[60] the oil palm concession location from (GFW, 2023),[72] and the Indonesian map of administrative units from Data.World.[73]

For the proximity analysis, we generated raster's Euclidean proximity from each covariate using Euclidean Distance derived from ArcGIS Pro 3.2. These rasters calculate the Euclidean distance from each pixel to the nearest feature of interest. For land covers, the proximity analysis is conducted for each year during 2015–2019, due to data availability, reflecting land cover changes during large scale fire events in Kalimantan, Indonesia. For the remaining years we used the values from 2019. As the end of process, all proximity rasters were processed at a 50 m resolution to ensure more accurate representation of land cover proximities. Finally, we aligned and merged all rasters with the *raster* package in R using the rewetted or treated areas layer as the base. Then we converted the multi-band raster to a csv database for applying the matching and DiD algorithms in R and Stata, respectively. Our full dataset with all canal blocks in both provinces contains 11.3 million observations and 31 variables.

QUANTIFICATION AND STATISTICAL ANALYSIS

Matching and balancing the dataset for the DiD counterfactual assessment

For the counterfactual analysis of avoided fires we balanced the data using the previously described climate, terrain, socioeconomic and fire history variables to match each treatment (rewetted) pixel to the most similar control (unrewetted) pixel found within 2 km circular buffers around all canal blocks. Concretely, we use prognostic and propensity scores for all years since block construction until 2022, and the fire occurrence in the two years before the block installation to find the most similar units based on mahalanobis distance near neighbor matching.

The prognostic score predicts the fire probability in treated areas had they never received the treatment. It allows to summarize all the different covariates affecting fire risk into one concrete metric avoiding placing equal weight for the match across several risk factors and covariates. The propensity score allows summarizing how all the variables affecting fire risk explain treatment assignment. Using both scores to find the best match has been shown to improve match quality and reduce bias.[74]

Summing up, we obtain the prognostic score function for each year 2017–2022 using a logistic fire risk model calibrated on all control pixels that never had a block installed. Then we predict the prognostic scores for both treated and control units. Having different prognostic score functions for each year gives us the flexibility to model how fire risk changes throughout time, concretely how it is much larger during the dry El Niño years and lower in normal and wet years.[75]

Next, for each construction vintage year in each province (West and Central) we implemented the following: (a) calibrate the propensity score (psm) using a logistic function on all treated an control pixels; (b) project the propensity score on the entire dataset for all years. Using psm for each province and vintage gives us the flexibility to capture different decision making processes in each province and construction year for placing the blocks; (c) perform one-to-one near neighbor matching with the mahalanobis distance with no replacement using the fire occurrence of the two previous years before block construction, the fire occurrence of critical drought year 2015, and the psm and prognostic scores since the construction year until 2022. Moreover, we did exact matching for kecamatan and peat depth. The entire procedure was implemented in R version 4.3.2 using the package *MatchIt*.

Pairing treatment and control observations on the fires that occured in two previous years and then on all prognostic and psm scores from construction until the last year of observations allows us to find the best possible unit for comparison in terms of fire history and the probable fires that would have occured if the blocks had not been implemented plus similar characteristics determining that those places could have also qualified for block construction under the BRGM program. To make the comparison even more conservative we restrict the search for matches to only pixels in the 2 km buffers in the same kecamatan and in peatlands with the same peat depth, as the amount of organic material available for combustion is a key factor for fires. We judge a match to be valid if the standardized mean difference of all the matching variables is less or equal than 0.2.

Using the psm and prognostic scores facilitates matching on specific key variables throughout the years but since those variables summarize the information of all key factors affecting fire occurrence, they also render a good balance of specific factors such as average monthly precipitation and distance to oil palm concessions (see supplemental information).

It's worth highlighting that our counterfactual approach for evaluating both types of canal blocks controls for confounding factors that are determinants of fire risk by finding the most similar comparison areas or pixels via matching, and then isolating the impact of the infrastructure with the multiple DiD procedure.

Identification of the causal effect of canal blocks on avoiding peat fires

We identified the causal effect of the canal blocks, and the subsequent water table raising and peat rewetting, on fires in peat land cover using the DiD for multiple time periods with staggered treatment adoption estimator proposed by Callaway and Sant'Anna.[43] This method allows us to do an Impact Evaluation using a credible statistical counterfactual of what would have happened had the canal blocks never been built.[42,76] The DiD estimator helps us to assess the impact of canal blocks by controlling for the fire history and dissimilarities in covariates that affect fire risk between treatment (rewetted) and control (unrewetted) pixels. Moreover, the Callaway and Sant'Anna[43] estimator goes beyond the traditional DiD approach by allowing inference of impacts for multiple time periods, different timing of canal block construction and having fire history parallel trends conditional on covariates affecting fire risk.

Since the canal blocks were not randomly implemented, we can only do the large scale evaluation of the program based on the quasi-experimental method of the DiD estimator in order to assess the average treatment effect on the treated (ATT) for the canal blocks built from 2017 to 2022 in peatlands of West and CK. We specify the following linear fire probability equation:

$$y_{ikt} = \beta_0 + \sum_{d\in D}\beta_d Dist_{iktd} + \sum_{c\in C}\beta_c Cli_{iktc} + \beta_g lights_{ikt} + \beta_n \sum_{l=1}^{4} y_{i-lkt} + \beta_t y_{ikt-1} + \varepsilon_{ikt} \qquad \text{(Equation 1)}$$

where: y_{ikt} is a binary variable registering fires in pixel i in village k in year t. The fire (1) or no fire (0) data was processed using the MCD64A1.061 MODIS Burned Area Monthly. β are the parameters to be estimated. $Dist_{iktd}$ is the distance to primary and secondary roads, rivers and land uses or cover of type d (primary, secondary and plantation forests, agriculture, mining and oil palm concessions). Cli_{iktc} are the c climate variables (ppt, temp). $lights_{iktg}$ is lights Intensity of night lights VIIRS which is a proxy for population density. y_{ikt-1} is a binary variable representing whether pixel i was on fire one year ago (time lag). y_{i-lkt} is a binary variable representing whether the i-l neighbor of pixel i was on fire in the same year t (spatial lag). We sum the spatial lags of the four neighboring pixels (north, south, east and west). ε_{ikt} is the random error term.

With the above equation we model the occurrence of fires as a function of climate, terrain, socioeconomics (distance to roads, land use and population density) and the time and spatial lags of fires. The variables determining fire occurrence were based on the literature.[28] We estimate fire probability functions for each year, implying that the parameters will vary by year, to have flexibility in modeling how fire risk changes across time, to capture annual variation in years such as the dry El Niño years compared to normal and wet years.[75]

This linear fire probability equation feeds into the larger average treatment effect on the treated (ATT) estimator for DiD proposed by Callaway and Sant'Anna.[43] Furthermore, the estimator we used is the doubly robust version, which means that it estimates the fire or outcome function and also weights it by the probability of receiving treatment (propensity score). Thus, either only the outcome function or the probability of receiving treatment have to be correctly specified and consistent to make the entire inference consistent and robust.

Controlling for the time and spatial lags of fires in the outcome equation allows us to capture whether a nearby area being on fire affects the probability of a pixel being on fire, and if the fire history of a pixel influenced the likelihood of current fires. The Callaway and Sant'Anna[43] estimator uses specific outcome functions (fire probability equations) for each period (year in this case) allowing us to model fires during very dry years (2019El Niño) differently from fires during normal years. We acknowledge that there can be temporal and spatial correlation in the random error so we use clustered standard errors at the village level in the DiD estimator.

In order to assess the heterogeneous impacts of canal blocks we created statistical counterfactuals, using the specifications described above, by kecamatan, year of construction, canal block type (wood or concrete) and rewetted area type (treated areas with or without overlaps). Our overall sample is 11.3 million observations, facilitating having enough statistical power to estimate the effect of canal block rewetting on fire occurrence for most of the specific counterfactuals and we report the statistical power for all statistically significant results at 95% CI (Tables S8–S88). We show and discuss in the main text (Results section) the outcomes for each counterfactual at the kecamatan level that was statistically significant at a 95% confidence interval and had a statistical power of 80%. While the matching done previously allowed us to have the same number of balanced treatment and control pixels in each kecamatan, when we create counterfactuals by overlap type, in certain cases, we have different number of controls than those of treatment pixels. Nevertheless, this is no impediment to proceed with the statistical inference as we are able to account for the impact of this difference when calculating the statistical power and if a result lacks a power of at least 80% then we do not report it as valid in the main and aggregate results but we report it in the SI (Results and Tables S8–S88). We ran the analysis in Stata 17 using the *csdid* command.

We applied our DiD counterfactual procedure to the balanced data where each treatment (rewetted) pixel was matched with the most similar control (unrewetted) pixel found within the 2 km circular buffers. Figure S16 depicts a summary of the counterfactual construction method.

Robustness checks

We conducted robustness checks using pixels from a further away control buffer (within a 4 km radius area) to assess the impact of canal blocks on avoided fires. We implemented the same matching procedures, but we could not find a valid comparison dataset that balanced all the requested variables with a standardized difference less or equal than 0.2 (see SI). Thus, control pixels further away than our preferred 2 km radius are not statistically similar to the rewetted areas and we cannot use them for building a credible counterfactual.

Calculating the avoided fire areas

We calculated the area of avoided peat fires due to the construction of effective canal blocks using the average ATT estimate from the DiD counterfactual assessment based on Eq. 1 which can be interpreted as the percentage reduction in burnings inside the treated area. We multiplied this estimate by the corresponding rewet area for each separate dataset based on the province or cluster of kecamatan, year of construction and material (wood and concrete) as explained in previous sections. Detailed results are in the subsection Supplementary Figures and tables for the main results of the supplemental information.

Projecting the scale up of best practices

We projected the benefits of canal blocking on fire occurrence and emissions assuming that the best practices could have been replicated in areas with a similar canal network density. First, we calculated in ArcGIS the canal network density inside the 2 km buffer control areas (km/km2) for each kecamatan. Then for each kecamatan with ineffective blocks, that had no statistically significant results, we assigned the projected impact of the effective kecamatan with the most similar canal network density regardless of whether the constructed blocks were wood or concrete. Therefore, we were able to project what would have been the avoided fire area if the feasible best practices would have been deployed in all kecamatan that had any canal blocks built from 2018 to 2022. Notice that our projection is conservative since it assumes that best practices would have been able to reduce fires only in the years that they did so according to the estimates from counterfactual. Detailed results are presented on Table S93 and we used the avoided fire area to calculate projected emissions reductions as explained in more detail below.

Reduced GHG fire emissions

We assessed the CO_2 and CH_4 emissions reductions due to avoided fires using the impacted area results explained in previous paragraphs, and environmental parameters from Novita et al.: burn depth (31.8 cm), soil bulk density (0.16 g cm^{-3}) and GHG emissions factors (1670.1 CO_2 g kg^{-1} and 8.47 CH_4 g kg^{-1}). To be conservative we assumed that only 54% of the affected mass of peat is actually combusted (0.54 combustion factor), based on Krisnawati et al.,[77] and we express everything in tCO_2e using the methane GWP for a 100-year horizon.[78]

Assessment of costs and benefits of reduced GHG fire emissions

For assessing the share of construction costs that could have been paid with GHG fire emissions reductions, the amount of monetary resources that could be generated to pay for the infrastructure cost, we used: (a) carbon offset prices of 10 USD/tCO_2e which is in the range of prices for NCS projects in 2022–2023[79] and of projections of voluntary carbon markets in 2030 and 2050,[80] (b) the midrange cost of concrete block construction (USD 11,750) from Hansson and Dargusch[81] and we assumed that wood blocks cost a third of that value, (c) the average real interest rate in Indonesia for 2012–2022 (6.53%) as the discount rate[82] and (d) the impacted area calculated as previously explained in the above sections.

We assessed the economic value of the fire related reduced GHG emissions using the parameters mentioned in the above paragraph and the social cost of carbon (100–150 USD/tCO_2e) instead of the carbon offset price. We used the reference value of 100–150 USD/tCO_2e since it has been applied in the NCS literature[83] and is in the low end of recent assessments of climate change impacts (median and average values of 185–417 USD/tCO_2e).[84,85]

We computed the percentage of the construction cost that could have been paid with offsets for the effective blocks that had a statistically significant impact. We assumed a 10-year time horizon that aligns with the expected infrastructure life cycle of canal blocks and extends the same schedule of emissions reductions from the first five years (2018–2022) through the 10-year life cycle (Table S94). Assuming the same rate of emissions reductions from the first five years (2018–2022) through the 10-year life cycle implies assuming the same climate and environmental conditions in the five final years than in our study period. For assessing the projected benefits of scaling up best practices we used the calculated emissions reductions described in previous sections, the 10-year life cycle, the social cost of carbon and the discount rate in order to obtain the internal rate of return (Tables S95 and S96).