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Rapid and lasting gains from solving illegal fishing

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Perhaps the greatest challenge facing global fisheries is that recovery often requires substantial short-term reductions in fishing effort, catches and profits. These costs can be onerous and are borne in the present; thus, many countries are unwilling to undertake such socially and politically unpopular actions. We argue that many nations can recover their fisheries while avoiding these short-term costs by sharply addressing illegal, unreported and unregulated (IUU) fishing. This can spur fishery recovery, often at little or no cost to local economies or food provision. Indonesia recently implemented aggressive policies to curtail the high levels of IUU fishing it experiences from foreign-flagged vessels. We show that Indonesia's policies have reduced total fishing effort by at least 25%, illustrating with empirical evidence the possibility of achieving fishery reform without short-term losses to the local fishery economy. Compared with using typical management reforms that would require a 15% reduction in catch and 16% reduction in profit, the approach of curtailing IUU has the potential to generate a 14% increase in catch and a 12% increase in profit. Applying this model globally, we find that addressing IUU fishing could facilitate similar rapid, long-lasting fisheries gains in many regions of the world.

Overfishing remains a major problem in many fishing countries, threatening food security, livelihoods and conservation[1–3]. While the future benefits of fishery reform are undeniable in these locales, perhaps the greatest threat to recovery is that it inevitably entails significant short-term reductions in fishing effort, catch and profit[1,4,5]. These short-term costs often prevent countries from undertaking reforms and may explain why so few countries, especially in Asia, have engaged in aggressive fishery reforms.

While illegal, unreported and unregulated (IUU) fishing is usually portrayed as an additional threat to fishery sustainability[1,2,6], we argue that a high level of IUU fishing by foreign fleets in a country could, instead, be its ticket to rapid and lasting fishery recovery. This is because when a country is plagued by high IUU fishing by foreign fleets, if it focuses first on eliminating this IUU fishing, this reduction often may be sufficient to facilitate recovery without lowering catch by the domestic (legal) fleet. In these cases, eliminating IUU fishing can allow countries to recover their overfished stocks without the usual short-term costs.

Data on IUU fishing are scarce in most countries, so we focused our empirical analysis on Indonesia, which is widely known to have been historically afflicted by high levels of IUU fishing. IUU fishing in Indonesia's exclusive economic zone (EEZ) has largely been carried out by foreign-flagged fishing vessels[7–9]. In recent years, the government responded by banning foreign fishing within its EEZ. Using new data from satellite technologies, we show that Indonesia's IUU policies effectively regulated foreign fishing, positioning the country well to implement fisheries management reform without incurring the costs that are typically associated with this process. Expanding beyond Indonesia, using regional-level estimates of fishery status and IUU fishing in other parts of the world, we project that

this approach can significantly narrow the gap to achieving global fisheries sustainability and can even bring some regions into the path of sustainability without reducing their catch or profit.

As demand for food from the sea rises, many countries seek to increase fisheries production and profit. This can be accomplished in the short term by increasing fishing effort, although this approach is eventually doomed due to overfishing. Another approach is to adjust fishing effort to levels that maximize long-term sustainable or economic yields. This approach often requires an initial reduction in fishing effort and therefore reductions in harvest and profit (referred to here as the 'valley of death') to allow recovery of fish stocks to an optimal, productive and profitable level. Increased harvest and profit can only be achieved in the future when stocks have recovered[1,4]. We show that a third approach is to eliminate IUU fishing, and that this approach can be the fastest and potentially longest-lasting way to increase fisheries production and profit while avoiding the 'valley of death'.

About 20% (11–26 million metric tonnes) of global fish catch is caught illegally, resulting in an annual global fisheries loss of US$10–23.5 billion[6]. In some regions, such as the western and central Pacific Ocean and eastern central Atlantic, illegally caught fish may constitute more than 30% of the total catch[6]. The enormous expansion of distant-water fishing (that is, fishing in international waters or other countries' EEZs)[10,11] has been accompanied by high incidences of IUU fishing activities in foreign territories, raising concerns for the sustainability of global fisheries[10–12].

New technological developments enable us to track the behaviour of individual fishing vessels globally and in near real-time, giving us an unprecedented window into potential IUU fishing activity[13]. China, South Korea and Taiwan were the top three flag states fishing in foreign EEZs between 2013 and 2016 (Fig. 1 and

Fig. 1 | Global network of distant-water fishing. Lines connect flag states (blue) fishing in foreign EEZs (red). The line thickness represents total fishing hours and the circle size represents the number of distinct foreign vessels fishing in different EEZs. Hotspots of foreign fishing activity can be seen in western Africa, the Indian Ocean and the western and central Pacific. Data were taken from the GFW (2013–2016).

Supplementary Fig. 1); each of these countries fishes in over 50 foreign EEZs (Fig. 1 and Supplementary Fig. 2) and has been implicated in several incidents of IUU fishing in foreign EEZs[11,14–16]. Indonesia—the world's leading producer of tuna and the second largest producer of marine wild capture fish[3]—loses US$4 billion a year in profits due to IUU fishing[17] and was ranked as the fifteenth and thirteenth most fished nation by foreign fleets in 2013 and 2014, respectively (Fig. 2). IUU fishing in Indonesia takes many forms, including—but not limited to—foreign boats that are authorized to fish but underreport the size of their boats to avoid monitoring and taxes; foreign boats disguising ownership under local names to take advantage of the Indonesian government's fuel subsidy; and foreign boats that falsify fishing permits and intrude in waters reserved for local, small-scale fishers[7].

Recently, Indonesia has taken a hard stance against IUU fishing by implementing policies designed to curb this activity within its EEZ. The new policies make use of three key approaches: sinking illegal vessels, banning foreign fishing vessels and banning transfers of fish at sea. Indonesia has sunk 318 fishing boats (primarily from Vietnam, the Philippines and Malaysia) engaged in illegal fishing activities since the implementation of their IUU policies (Supplementary Fig. 3). Indonesia also implemented two consecutive six-month moratoria on vessels of foreign origin registered in Indonesia, starting in November 2014. As soon as the country stopped renewing annual fishing permits to these vessels, 1,132 foreign-owned or foreign-made vessels were prohibited from fishing

in Indonesian waters. Transshipment at sea, or the transfer of fish between boats, was also banned by Indonesia in 2014 because transshipment can mask where and by whom fish are caught. The local, legal fleet has since been allowed to resume transshipment at sea, provided boats comply with stringent regulations requiring an onboard observer, a vessel monitoring system (VMS) and onboard closed-circuit television cameras. Fishing and transshipping activities by foreign boats are still banned.

While Indonesia's IUU policies are novel and bold, little rigorous analysis has been undertaken to evaluate the efficacy of these policies in controlling IUU fishing activity or to determine whether these policies have had a demonstrable effect on Indonesian fish stocks and the fisheries economy. Because similar analyses have not been undertaken elsewhere, it has thus far been impossible to test empirically whether eliminating IUU fishing could allow countries to recover fisheries at little or no cost to local fishers. We use the skipjack tuna fishery as a model case study to estimate the economic and conservation effects of Indonesia's IUU policies. Skipjack tuna is the largest fishery in Indonesia by volume[18] and 43% of government-registered industrial fishing boats are purse seine boats[19], most of which target small pelagic species and skipjack tuna, often using lights and fish aggregating devices to attract fish.

Results and discussion

Before the IUU policies, skipjack tuna biomass was above the level of biomass at maximum sustainable yield (MSY), although catch
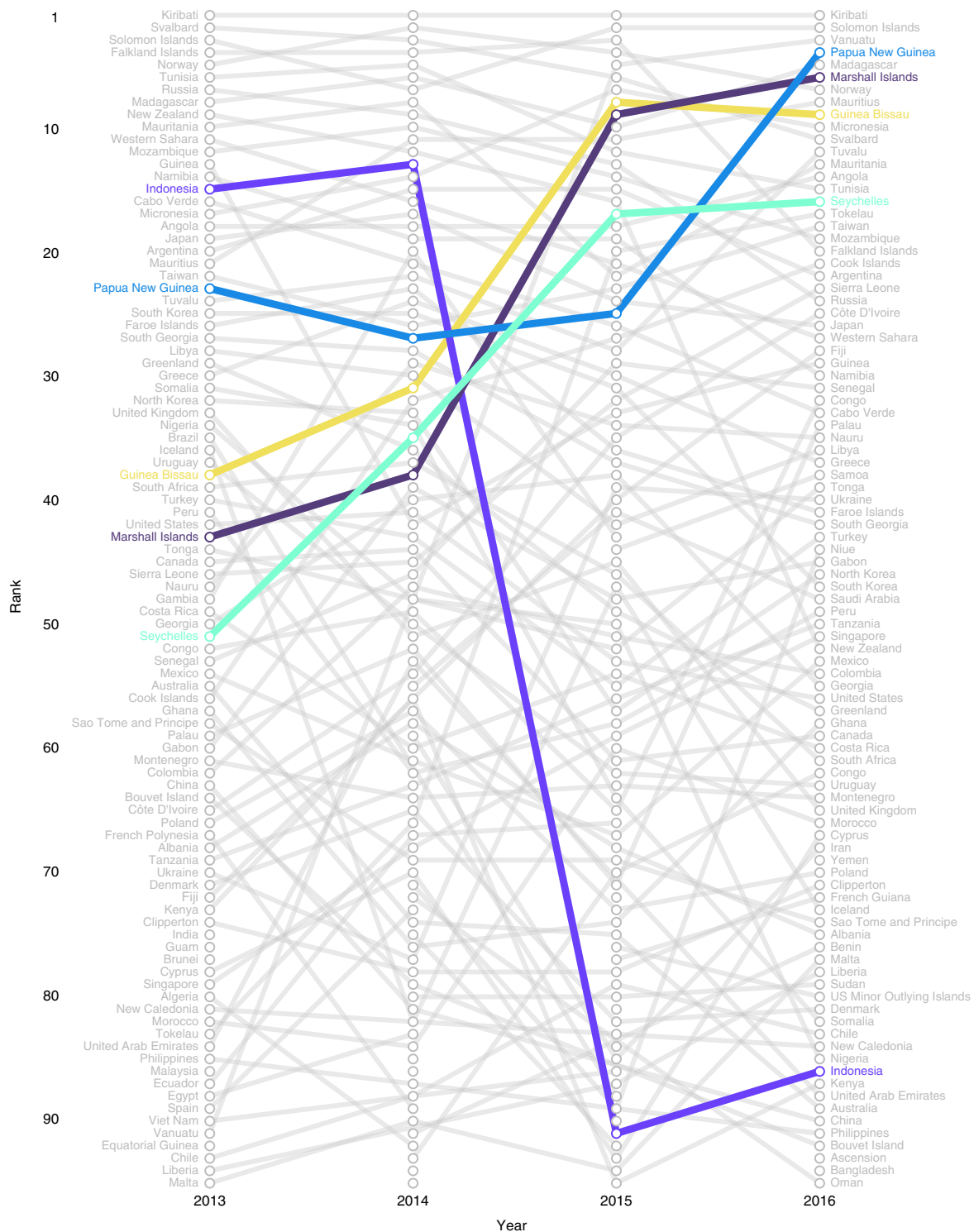
Fig. 2 | Top 95 most fished EEZs in 2013 and the evolution of their rankings through time. EEZs are ranked in terms of total fishing hours carried out by foreign distant-water fleets within their waters. For example, Vanuatu's ranking was fifth in 2015 and third in 2016. In 2013 and 2014, its rank was >90 (2014 ranking not shown).

was 17% above MSY (Supplementary Tables 1 and 2). The moratorium on foreign vessels reduced the number of fishing boats over 30 gross tonnes (GT) in Indonesia by 27% (from 4,286 boats[20] to 3,114 boats[19]). This represents a 40% reduction in fishing effort as measured by boat weight (Supplementary Table 3), with the reduction in fishing pressure due in large part to the decrease in boats from the largest size classes fishing in Indonesian waters (that is, those

>100 GT) (Fig. 3a). Although this action alone may have substantially reduced fishing mortality rates, Indonesia's fishing policies are not motivated solely by the desire to reduce illegal fishing. An additional objective is to increase the capacity of the domestic Indonesian fleet. Indonesia is currently building 3,325 new fishing boats and aims to distribute 13,872 sets of fishing gear to local fishers by 2019. Of the new boats, five are 30 GT transshippers, 30 are 30 GT fishing
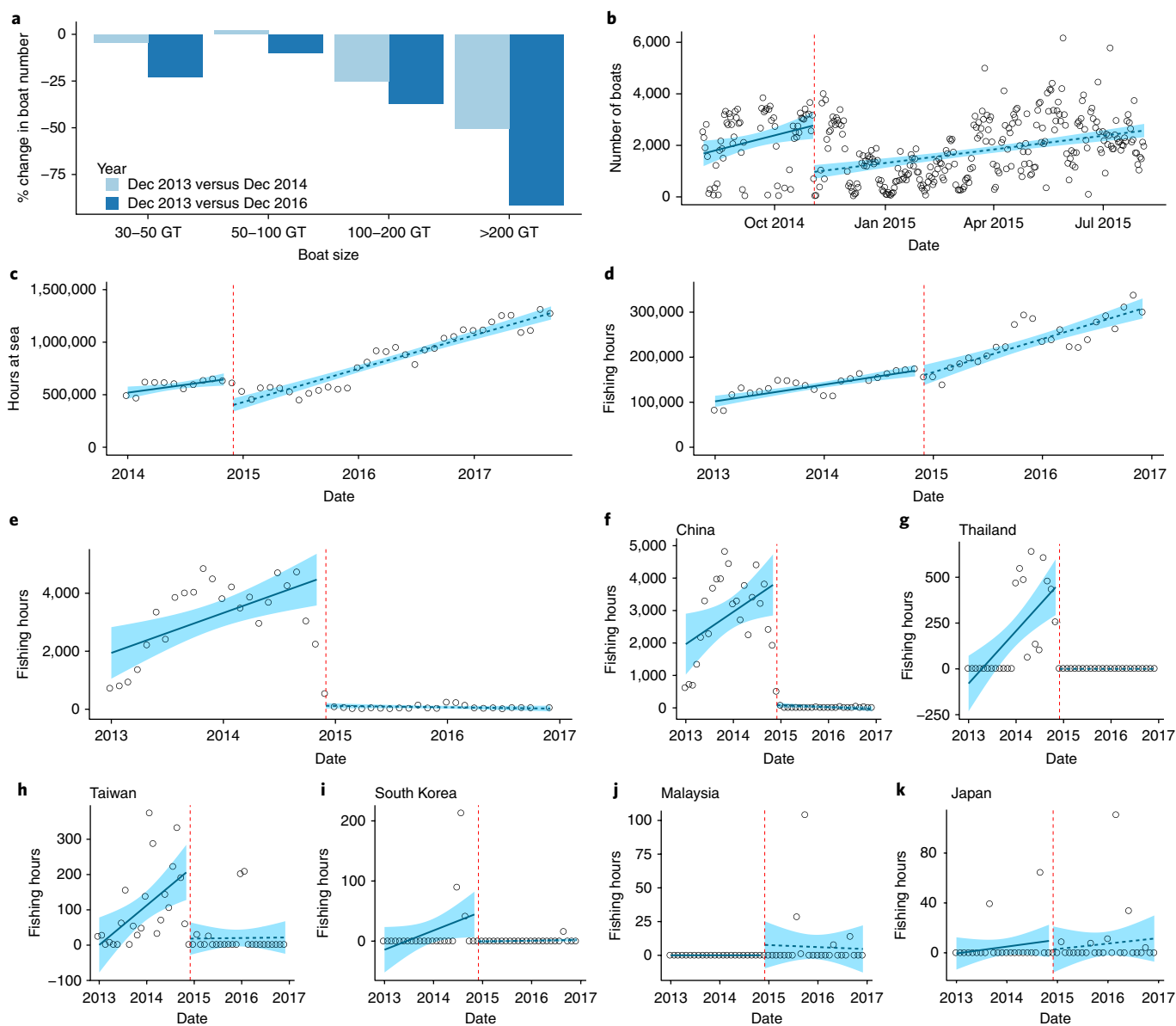
Fig. 3 | Fishing effort before and after the implementation of Indonesia's IUU policies. a, Percent change in boat number by size class before (2013) and after (2014 and 2016) the implementation of moratoria on foreign fleets. Data are derived from Indonesia's boat registration records. **b**, Number of boats detected within Indonesia's EEZ, based on nightlight satellite images. **c**, Total hours at sea per month of fishing boats. Data are derived from Indonesia's VMS data. **d**, Fishing hours per month of all countries fishing in foreign EEZs, using AIS data from the GFW. **e**, Fishing hours per month of foreign boats fishing in Indonesia, using AIS data from the GFW. **f–k**, Fishing hours per month of the top foreign nations fishing in Indonesia, using AIS data from the GFW. The vertical dashed red line represents the beginning of the implementation of Indonesia's IUU policies; the solid blue line represents linear regression of data before the IUU policies; the dashed blue line represents linear regression of data during the IUU policies; and the blue shading represents the 95% confidence interval.

boats and the rest are <30 GT fishing boats. Therefore, the new vessels will have a much smaller size distribution than the foreign boats they replace. Despite this increase in domestic fishing capacity, we estimate that net fishing pressure will still decline by 25–35% relative to conditions before the IUU reduction actions (see Methods).

To study the extent to which fishing effort has been reduced by IUU policies, we analysed three different empirical datasets: (1) satellite data of nightlights; (2) publicly accessible automatic identification system (AIS) data from anticollision signals processed through Global Fishing Watch (GFW; http://globalfishingwatch.org/); and (3) VMS data provided by the Indonesian government. The number of boats detected from nightlight images confirms a

30% decline in the total number of boats immediately following the implementation of the moratorium, suggesting that Indonesia's IUU policies are working (Fig. 3b; see Methods). An analysis of the AIS data showed a striking >90% reduction in the fishing hours of foreign boats in Indonesia, with most of the reduction from China, Thailand, Taiwan and South Korea (Fig. 3e–k). There was no apparent decline in fishing from Malaysia and Japan, but the fishing effort from these countries was small before the IUU policies (0–100 h month[−1]) relative to that of China (2,000–5,000 h month[−1]). Consequently, Indonesia's ranking in the list of nations that are most fished by foreign boats dropped from fifteenth in 2013 and thirteenth in 2014
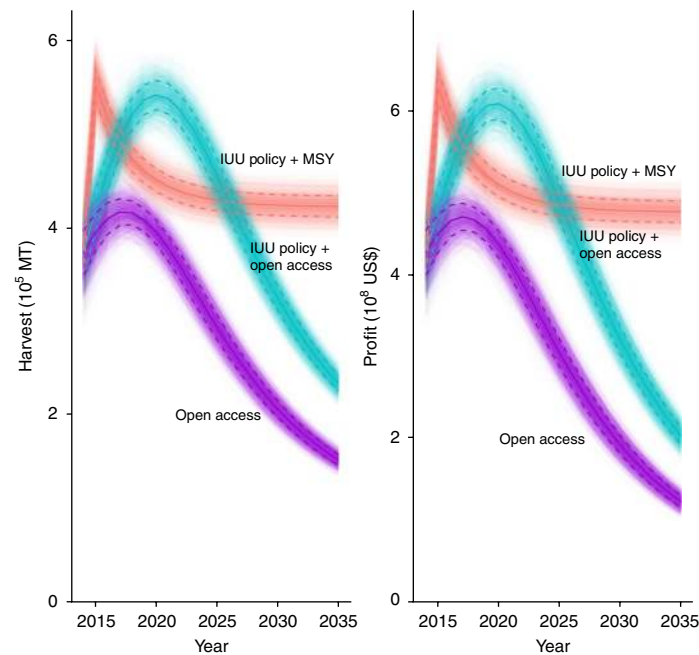
Fig. 4 | Benefits of addressing IUU fishing in Indonesia. Indonesia's local skipjack harvest and profit under the scenarios of an open-access fishery (business as usual), implementation of IUU policies but uncontrolled domestic effort expansion, and implementation of IUU policies and targeting effort expansion at the MSY level. The background shading represents the 1,000 projections derived from bootstrapped population parameters; the solid lines are the mean values; and the dashed lines represent s.d. from the mean.

to below eightieth in 2015 and 2016 (Fig. 2). This reduction in foreign fishing in Indonesia has persisted despite the continuous increase in distant-water fishing effort globally[11,21] (Fig. 3d). Interestingly, the nightlight satellite analysis reveals that fishing effort in Indonesia increased during the extension of the moratorium in mid-2015 (Fig. 3b). Given that the foreign fishing effort in Indonesia remained at low levels (Fig. 3e), it appears that domestic fishing may be expanding to replace international fishing pressure. This hypothesis is supported by the increasing trend in domestic effort shown by the VMS data (Fig. 3c). The larger increase in local fishing effort following the introduction of the IUU policies as shown by the VMS data compared with the nightlight analysis can be explained by the increase in VMS installations after the IUU policies, both as a result of increased compliance and an increased number of local boats (Supplementary Table 4). These findings suggest that removing international fishing pressure alone may not be a sufficient solution for sustaining Indonesia's fisheries. Increased domestic effort, if not managed effectively, may negate the positive ecological and economic impacts of anti-IUU policies.

We developed a bioeconomic model to evaluate changes in harvest and profit resulting from various IUU and domestic reform management scenarios (see Methods). Our modelling scenarios indicate that if an open-access regime is maintained and no IUU policies are implemented, Indonesia could experience a 59% decrease in catch and a 64% decrease in profit by the year 2035 compared with the present levels (Fig. 4). If IUU policies are implemented (assuming a 25% reduction in fishing effort), but domestic fishing effort remains unmanaged, Indonesia's skipjack catch and profit will decline by 37 and 52%, respectively, by 2035 (Fig. 4). However, if IUU policies are implemented and domestic fishing effort is regulated appropriately to achieve MSY, we forecast that Indonesia's skipjack catch and profit could increase by 14 and 12%, respectively, by 2035 compared with current levels (Fig. 4). Setting harvest at MSY without addressing IUU fishing—assuming the very unlikely scenario of sustained optimal yield in the presence of IUU fishing—can result in 15 and 14% reductions in catch

and profit, respectively. Our projected profit increase as a result of Indonesia's IUU policies is conservative as it does not account for benefits that could be derived from greater market efficiencies or sustainability premiums.

Our analysis highlights the importance of quantifying the reduction in fishing effort a country achieves through IUU policies, as it informs the extent to which a country could sustainably expand domestic fishing effort in the future. Satellite-based technologies can facilitate evaluation of the immediate and future impacts of policies that affect fishing pressure within and beyond EEZs[22]. Furthermore, these technologies allow monitoring of distant-water fishing globally, which will be important given the enormous expansion of this type of fishing activity (Fig. 3d). For example, steep increases in distant-water fishing in Vanuatu, Papua New Guinea, Guinea-Bissau, the Marshall Islands and the Seychelles suggest that greater scrutiny is needed to control foreign fishing activities in these countries (Fig. 2). Although regions with high IUU fishing correspond to distant-water fishing hotspots (Fig. 1), high foreign fishing within an EEZ does not necessarily equate to high levels of IUU fishing. For example, the sharp increase in fishing effort in Guinea-Bissau is due to the government granting licences to foreign fishing vessels. Countries can grant access to foreign fishing fleets, but the experiences of several African countries[23,24] suggest that high levels of distant-water fishing often result in high levels of IUU fishing. In the case of The Gambia, distant-water fishing produced minimal benefits to the local economy and resulted in higher levels of IUU fishing[25].

Even though AIS data from the GFW provide an unprecedented view of the spatial and temporal patterns of global distant-water fishing, this dataset is limited by the fact that not all fishing vessels in the world carry AIS. As more countries have adopted AIS regulations and more satellites are being used for ocean monitoring, the number of distant-water vessels in the GFW database has nearly doubled in the past few years, from 3,681 in 2013 to 6,105 in 2016. Lower AIS coverage in 2013 and 2014 may have underestimated the extent of foreign fishing effort pre-IUU policies in Indonesia.
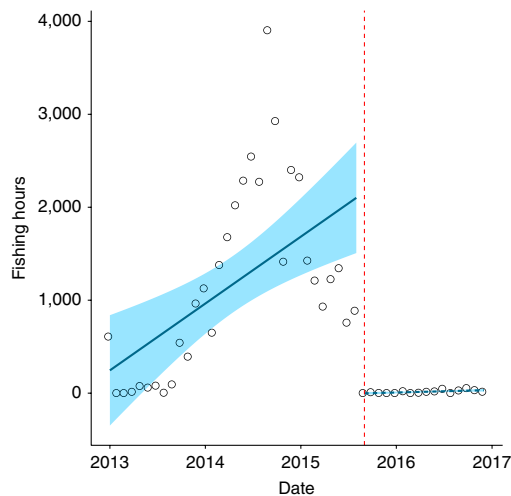
Fig. 5 | Distant-water fishing in The Gambia. The Gambia banned all industrial fishing between late 2015 and mid-2017. The vertical dashed red line represents the beginning of the implementation of The Gambia's policy; the solid blue line represents linear regression of data before the policy; the dashed blue line represents linear regression of data during the policy; and the blue shading represents the 95% confidence interval.

This suggests that our estimate of effort reduction in Indonesia is probably conservative.

Through our case study, we have found that Indonesia's IUU policies have reduced fishing effort to a level where limited expansion in domestic (legal) fishing effort can occur without undermining fishery sustainability. Had Indonesia's IUU policies only minimally reduced fishing effort, the country would not be able to expand its legal domestic fleet without compromising fishery benefits. An unfavourable outcome of this kind transpired in the United States following the 1976 implementation of the Magnuson–Stevens Act—an act that removed all foreign fishing vessels from the US EEZ. Through this policy, the United States effectively eliminated IUU fishing activity by foreign vessels. However, overinvestment in domestic fishing capacity prevented many stocks from recovering[26]. Subsequent revisions to the Act in 1996 and 2007 set most fisheries on a trajectory towards sustainability[27].

Although our analyses focus primarily on industrial-sized boats, addressing IUU fishing and the open-access nature of small-scale fisheries should also be a priority. For example, in Raja Ampat in eastern Indonesia, IUU fishing accounted for 37–93% of the harvest of reef fishes, invertebrates, tuna and small pelagic fishes in 2006, resulting in losses of US$40 million[28]. Illegal and destructive fishing methods such as blast fishing, cyanide fishing and compressor diving accounted for 20% of the total reef fish catch in 2006 (ref. [28]). These IUU activities in Raja Ampat caused overfishing, serial depletion of reef species and losses in government tax revenues; most of the gains were captured by fishers residing outside Raja Ampat.

While our Indonesia study focuses mainly on IUU fishing by foreign fleets, about 7% of the 318 IUU boats sunk by Indonesia (22 boats in total) are Indonesian flagged, illustrating that Indonesia is also tackling IUU fishing by domestic vessels. Furthermore, Indonesia's decision to make its VMS data publicly available is another indication of its commitment to combating domestic IUU fishing. Other management measures implemented by Indonesia to improve its local fisheries include a capture ban on undersized and egg-bearing crustaceans, a ban on trawl-like fishing gears, improvements in fishery registration and data management, and several market-related measures (some of which target IUU fishing by improving traceability in seafood supply chains).

Indonesia is not the only country that has implemented strong measures to address IUU fishing. The Gambia, which has historically experienced high levels of IUU fishing from foreign industrial fleets, banned all industrial fishing in its EEZ from late 2015 to mid-2017 (ref. [23]). We analysed The Gambia in a manner that tracks our Indonesia case study. We found that The Gambia's policies, which targeted both IUU fishing and corruption in its fisheries department, had effects similar to those of Indonesia's IUU policies. Following the ban, there was almost zero foreign fishing in The Gambia's EEZ (Fig. 5). Using the heavily targeted, high-value common octopus as our model species, we show that The Gambia's IUU policies could also result in higher local fish catch and fishery profit (see Supplementary Information).

Through the two case studies of Indonesia and The Gambia, we demonstrate across different country contexts that when a country is plagued by high levels of IUU fishing by foreign fleets, addressing IUU fishing can drive fisheries recovery without reducing local catch and profit. For cases where IUU fishing is dominated by local fishers, addressing IUU fishing can result in local losses in catch and profit. A strong motivation for addressing all forms of IUU fishing is that high levels of IUU fishing undermine fisheries management efforts and lead to overexploitation of stocks if not accounted for or addressed. Combatting IUU fishing offers other ancillary livelihood benefits not addressed in our analysis, such as improving working conditions for crew and eliminating human rights abuses, such as the use of slave labour, which can be prevalent among IUU vessels. Nonetheless, governments should include pro-poor measures that provide an economic safety net to local fishers and make legal forms of fishing more lucrative and attractive, as tough measures against illegal fishing often negatively impact fishers, especially the poorest. Indonesia's plan to distribute boats and gears to local fishers is a pro-poor programme, but should be implemented with caution as such programmes can further degrade already overfished fisheries, as has happened in some areas of Southeast Asia.

Although local fishers need not bear the cost of reform in Indonesia, continuous investment in monitoring, control and surveillance is needed to maintain an IUU-free EEZ. Indonesia's IUU policies have simplified enforcement, and when a foreign fishing boat enters its EEZ the Indonesian government can inspect it immediately. A cost–benefit analysis of Indonesia's VMS programme that assumes a modest impact on reducing IUU fishing forecasts significant fisheries benefits for Indonesia[29]. This projection does not account for the benefits obtained from increased fish stock productivity, improved fish prices or a reduction in wasteful fisheries subsidies. Partnerships between the government of Indonesia and international organizations such as the GFW also support monitoring, control and surveillance efforts in Indonesia's EEZ. Lastly, private philanthropists have demonstrated deep support for Indonesia in its mission for sustainable fisheries, and these policies may plausibly benefit international companies that source several key seafood products from Indonesia.

We demonstrate that taking a tough stance on IUU fishing can produce rapid improvements in fishery profits and catches and create an opportunity for a country to reform its fisheries while avoiding many of the short-run costs of cutting back significantly on domestic fishing efforts and catches. Indonesia's IUU policies concurrently address a number of associated important issues, such as human rights violations, illegal trade and smuggling and human trafficking[30]. However, securing long-term productivity and profitability of fisheries requires continuous efforts to dissuade IUU fishing by foreign fleets, and management of domestic effort to avoid overcapitalization.

Are the apparent benefits of eliminating IUU fishing unique to Indonesia and The Gambia, or can this approach be used to catalyse fishery recovery globally? We used existing regional estimates of IUU fishing[6] and fisheries status[1] to provide a rough estimate of
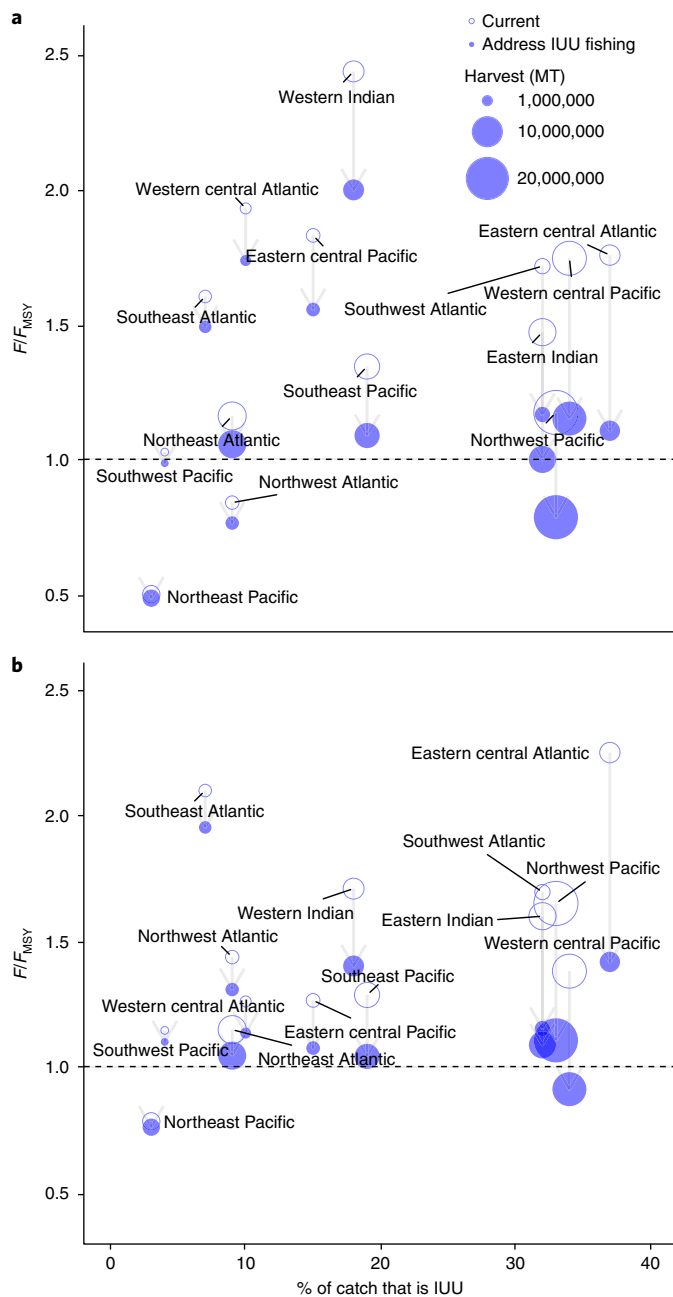
Fig. 6 | Potential benefits of addressing IUU fishing. When $F/F_{MSY} = 1$ (dashed line), fishing pressure is at the level that would result in MSY. $F/F_{MSY} \leq 1$ is desired for sustainable fisheries. Data for the fishery status per region are taken from ref. [1] and estimates of IUU fishing are from ref. [6]. **a**, F/F_{MSY} values of the median fishery per region. **b**, F/F_{MSY} values of the catch-weighted average fishery per region (see ref. [1]). The reduction in fishing pressure as the result of addressing IUU fishing is assumed to be proportional to the level of IUU fishing. Circle size represents marine capture production in the region in 2014 (ref. [3]).

these effects globally. Most regions of the world currently experience fishing pressure above the sustainable level (current fishing pressure, F relative to the fishing pressure that would result in MSY, $F_{MSY} = 1$) (Fig. 6). If IUU fishing were addressed in all regions, the gap to global fishery sustainability would narrow significantly, and fisheries reform would become much more feasible (Fig. 6). As was the case for Indonesia and The Gambia, addressing IUU fishing in many regions (that is, the northwest Pacific, eastern Indian,

southwest Pacific and western central Pacific oceans) could be sufficient to recover fisheries to sustainable exploitation levels while avoiding the dreaded 'valley of death'.

Methods

Parameter estimates for the bioeconomic model. Using the catch time-series data (1971 to 2014) for skipjack tuna *Katsuwonus pelamis* (Supplementary Table 1), we apply a Pella–Tomlinson[31]-based catch–MSY method[32] to derive estimates of population carrying capacity (K), growth rate (g), biomass and fishing mortality[1] (Supplementary Table 2). The biomass transitions of the basic surplus production model (that is, the Pella–Tomlinson model) are given by

$$B_{t+1} = B_t + \left(\frac{\varnothing + 1}{\varnothing}\right) g \; B_t \left(1 - \left(\frac{B_t}{K}\right)^{\varnothing}\right) - H_t \tag{1}$$

where t is time in years, $\varnothing$ is a growth parameter and H is the harvest. H is defined as $H = BF$, where F is the fishing mortality. The MSY for the fishery is given by $\text{MSY} = gB_{MSY}$, where $B_{MSY} = \frac{K}{(\varnothing + 1)^{\frac{1}{\varnothing}}}$. The fishing pressure that would lead to MSY is given by $F_{MSY} = g$ (ref. [1]).

We used the following priors for the catch–MSY model: $B_{1971} = 0.75$–$0.99K$ as the catch in 1971 is just 3% of the maximum catch (H_{max}) in the time series, $K = H_{max}$ to $20H_{max}$, and $B_{2014} = 0.25$–$0.75K$. Note that if $\varnothing = 1$, equation (1) becomes the Schaefer model with the Schaefer model growth rate $r = 2g$. The range of r values suggested in ref. [32] for a medium resilience species (http://www.fishbase.org/summary/107) is 0.2–1. Therefore, our g prior is 0.1–0.5. All priors are uniformly distributed. These priors follow the suggestion of ref. [32]. We show that these estimates (g, K, B and MSY) are robust to different ranges of priors (Supplementary Fig. 4).

Bioeconomic model. We used the transformed version of the Pella–Tomlinson model to forecast the population of skipjack tuna for different policy scenarios. Using $b_t = \frac{B_t}{B_{MSY}}$ and $f_t = \frac{F_t}{F_{MSY}}$, we reduced the population model to two biological parameters (g and $\varnothing$), a response parameter (b) and a control parameter (f). When $b = 1$, the biomass is at the level where the harvest is at MSY and $f = 1$ indicates that the fishing pressure is at the level that would result in MSY.

The equations describing biomass (b), profit (π) and harvest (H) are given by:

$$b_{t+1} = b_t + \left(\frac{\varnothing + 1}{\varnothing}\right) gb_t \left(1 - \frac{b_t^{\varnothing}}{\varnothing + 1}\right) - gf_t b_t \tag{2}$$

$$\pi_t = pf_t b_t \text{MSY} - c(gf_t)^{\beta} \tag{3}$$

$$H_t = f_t \; b_t \; \text{MSY} \tag{4}$$

where p is the ex-vessel price of fish, c is the variable fishing cost per unit of fishing mortality and β is the nonlinear fishing cost constant[1].

For an open-access fishery, f is given by:

$$f_{t+1} = f_t + \frac{\lambda \pi_t}{\pi_{MSY}} \tag{5}$$

$$\pi_{MSY} = p\text{MSY} - cg^{\beta} \tag{6}$$

where λ describes the entry–exit dynamics of fishers to the fishery and π_{MSY} is the profit at MSY.

We ran our bioeconomic model for Indonesia's skipjack tuna fishery under different management scenarios up to the year 2035. We derived the bounds of uncertainty of our projections by subsampling (bootstrap sampling) 100 data points per model parameter drawn from the posterior distributions of g, b, f and MSY derived using the catch–MSY method, calculated the geometric mean values of the subsampled parameters and repeated this process 1,000 times to derive 1,000 mean values of g, b, f and MSY.

Number of boats estimate. There were 4,286 boats (>30 GT) registered with the central government of Indonesia in 2013 (ref. [20]) (see Supplementary Table 3). A recent list (March 2016) showed that there are now 3,114 boats (>30 GT) registered[19]. The reduction in the number of boats is 1,172 (a 27% decline); this is close to the reported 1,132 foreign-made or -owned vessels affected by the moratoria. Fishing licences are renewed every year. A six-month moratorium on foreign fleets was implemented on 3 November 2014, followed by an extended moratorium for another six months. Therefore, fishing permits of all foreign vessels expired after the moratoria, justifying the use of the 2016 data. The 2014 data previously demonstrated an 11% reduction in the number of registered vessels

compared with the 2013 data, indicating that some of the licences of the 1,132 foreign boats had already expired at the end of 2014. In terms of boat weight, we observed a 40% reduction in total boat weight (mostly from boats >100 GT) in Indonesia after the implementation of the moratoria. Satellite image analysis indicated a 35% decline in fishing boats (average before IUU policies, 2,208 boats; average after, 1,425 boats; t-test, $P < 3.9 \times 10^{-6}$; Supplementary Fig. 5). We also confirmed this decline using a linear regression model (Supplementary Table 5). Our dependent variable was the number of boats detected at night. We ran three separate regression models, where each model included an indicator variable for the moratorium on foreign vessels. We controlled for trends and seasonality by including month indicator variables, year indicator variables and a rainy season indicator (fishing conditions are not very good during the rainy season). The estimated reduction due to the moratorium ranged from 20 to 50%, with most estimates centred around 20% (see below for details).

We used a 25% reduction in the fishing effort due to the moratoria on foreign fleets in our analysis. A 25% decline in effort is conservative even when accounting for the planned increase in local fishing capacity of 35 (30 GT) boats.

Analysis of nightlight satellite images. Ref. [33] describes the algorithm to convert satellite imagery of lights at night into detections of fishing vessel locations. Briefly, their algorithm reports the location, brightness and viewing conditions of lit fishing boats using Visible Infrared Imaging Radiometer Suite low-light imaging data from the Suomi National Polar-orbiting Partnership satellite launched in 2011. The algorithm works as follows. First, a radiance spike detection algorithm generates the boat detection candidates. Second, a second spike detection algorithm is used to discard detector noise and confirm the boat detections. Third, a sharpness index is used to screen out detections that lack the sharp profiles characteristic of boat detections. Finally, the candidate spikes are filtered to remove known non-boat features, such as lights on land and gas flares.

Nightly results are posted on the National Oceanic and Atmospheric Administration website and are available for a number of countries, including Indonesia. Results are often available four hours after collection. The algorithm works particularly well on nights with low lunar illuminance[33]. For example, on a new moon night in Indonesia, the system typically detects 5,000–6,000 boats per night. The data have known limitations based on the sensor characteristics. It is not possible to distinguish different types of lighting (for example, light-emitting diode versus incandescent), which might indicate different gear types or target species. It is also not possible to reliably estimate the size or number of boats present in an approximately 0.55 km² pixel. Under full moon conditions, large numbers of false detections arise from brightness variations in the clouds.

Based on the assumption that the nightlight data are a good proxy for fishing effort in the small pelagic fishery (both legal and illegal fishing effort), we can use these data to evaluate the impacts of fisheries management policies. In particular, we tested the impact of the six-month moratorium on ex-foreign vessels introduced in late 2014. Our dataset consists of the number of fishing boats detected at night for every night from 1 April 2012 until 31 December 2015 (1,366 observations) and a number of indicator variables for the moratorium, month, year and rainy season. We explored in a linear regression framework whether the number of boats detected during the moratorium is more or less than we would expect based on monthly and annual trends. The regression results in Supplementary Table 5 confirm that the moratorium results in the detection of fewer fishing boats. The estimated effect ranges from a 20 to 50% reduction relative to 2013 and is always statistically significant at the 5% level or better. Our preferred specification is column 3 of Supplementary Table 5 and includes controls for annual and seasonal trends (indicator variables for each year and an indicator variable for the rainy season); the estimated reduction in fishing boats detected is 19.96%. All regression models use standard errors adjusted for potential heteroscedasticity. Thus, we conclude that the moratorium had a noticeable impact on fishing effort in fisheries that use lights to attract small pelagic species.

VMS and AIS data from the GFW. We used the GFW publicly available AIS dataset to construct a dataset of foreign distant-water fishing effort during 2013–2016. We defined foreign distant-water fishing as fishing activity that occurs within an EEZ of a nation different from a vessel's flag state. We excluded from this dataset vessels fishing in conflict, disputed or joint-regime zones in which their flag's state was involved. For example, Japanese and Russian vessels fishing in the Kuril Islands (a conflict zone between Russia and Japan) were excluded. We also excluded vessels fishing in territories over which their flag state holds sovereignty. For instance, a vessel flagged in Réunion (a French overseas territory) fishing in the French Southern and Antarctic Lands or a UK-flagged vessel fishing in Ascension were excluded from the dataset. Finally, we excluded all fishing activity in European Union (EU) waters by EU-flagged vessels, as well as fishing activity under the EU northern agreements with Norway and Iceland.

For each vessel observed fishing in a foreign EEZ for at least one day, we estimated the total number of fishing days and fishing hours spent in each foreign EEZ. We obtained each vessel's flag state and gear type from the GFW database and cross-checked the information with other online databases (for example, the Food and Agriculture Organization vessel finder, Marine Traffic and Regional Fisheries Management Organisation registries) when the vessel's identity seemed

dubious (for example, vessels fishing in Brazil's EEZ and claiming to be flagged in Palestine). Most of the vessels with suspicious flags spent more than 90% of the time in China's EEZ and are likely to be Chinese vessels. Thus, we excluded from the analysis all vessels that spent more than 50% of their time in China's EEZ but claimed to be flagged elsewhere. Details on the GFW database, including the methods used to identify fishing gear and flag states and to estimate fishing effort, can be found in ref. [13]. We used the same method to derive the fishing hours of boats tracked by the VMS of Indonesia.

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Author contributions

All authors contributed to research design. Analysis was undertaken by R.B.C., J.M., J.L. and C.C. All authors contributed to writing the manuscript.

Competing interests

The authors declare no competing interests.

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☐ Initial submission   ☐ Revised version   ☒ Final submission

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▶ Experimental design

1. Sample size

    Describe how sample size was determined.

    | Analysis in this study was conducted using the full dataset available. |

2. Data exclusions

    Describe any data exclusions.

    | No data was excluded except in Figure 1. All data exclusions for generating Figure 1 are fully explained in the Methods, e.g. "We exclude from this dataset vessels fishing in conflict, dispute, or joint regime zones in which their flag's state is involved. For example, Japanese and Russian vessels fishing in the Kuril Islands (conflict zone between Russia and Japan) are excluded." |

3. Replication

    Describe whether the experimental findings were reliably reproduced.

    | All attempts at replication were successful. |

4. Randomization

    Describe how samples/organisms/participants were allocated into experimental groups.

    | Randomization was not relevant to our study. No manipulative experiments involving live subjects were conducted in this study. |

5. Blinding

    Describe whether the investigators were blinded to group allocation during data collection and/or analysis.

    | Blinding was not relevant to our study. No manipulative experiments involving live subjects were conducted in this study. |

    Note: all studies involving animals and/or human research participants must disclose whether blinding and randomization were used.

6. Statistical parameters

    For all figures and tables that use statistical methods, confirm that the following items are present in relevant figure legends (or in the Methods section if additional space is needed).

n/a	Confirmed	
☒	☐	The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement (animals, litters, cultures, etc.)
☒	☐	A description of how samples were collected, noting whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐	A statement indicating how many times each experiment was replicated
☒	☐	The statistical test(s) used and whether they are one- or two-sided (note: only common tests should be described solely by name; more complex techniques should be described in the Methods section)
☒	☐	A description of any assumptions or corrections, such as an adjustment for multiple comparisons
☐	☒	The test results (e.g. P values) given as exact values whenever possible and with confidence intervals noted
☐	☒	A clear description of statistics including central tendency (e.g. median, mean) and variation (e.g. standard deviation, interquartile range)
☐	☒	Clearly defined error bars

    See the web collection on statistics for biologists for further resources and guidance.

▶ Software

Policy information about availability of computer code

7. Software

Describe the software used to analyze the data in this study.

All graphs were generated using the free software R (version 3.3.2).

For manuscripts utilizing custom algorithms or software that are central to the paper but not yet described in the published literature, software must be made available to editors and reviewers upon request. We strongly encourage code deposition in a community repository (e.g. GitHub). *Nature Methods* guidance for providing algorithms and software for publication provides further information on this topic.

▶ Materials and reagents

Policy information about availability of materials

8. Materials availability

Indicate whether there are restrictions on availability of unique materials or if these materials are only available for distribution by a for-profit company.

No unique materials were used in this study.

9. Antibodies

Describe the antibodies used and how they were validated for use in the system under study (i.e. assay and species).

No antibodies were used in this study.

10. Eukaryotic cell lines

a. State the source of each eukaryotic cell line used.

No eukaryotic cell lines were used in this study.

b. Describe the method of cell line authentication used.

No eukaryotic cell lines were used in this study.

c. Report whether the cell lines were tested for mycoplasma contamination.

No eukaryotic cell lines were used in this study.

d. If any of the cell lines used are listed in the database of commonly misidentified cell lines maintained by ICLAC, provide a scientific rationale for their use.

No commonly misidentified cell lines were used in this study.

▶ Animals and human research participants

Policy information about studies involving animals; when reporting animal research, follow the ARRIVE guidelines

11. Description of research animals

Provide details on animals and/or animal-derived materials used in the study.

No animals were used in this study.

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12. Description of human research participants

Describe the covariate-relevant population characteristics of the human research participants.

The study did not involve human research participants.