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Complementing carbon prices with technology policies to keep climate targets within reach

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Economic theory suggests that comprehensive carbon pricing is most efficient to reach ambitious climate targets[1], and previous studies indicated that the carbon price required for limiting global mean warming to 2 °C is between US$16 and US$73 per tonne of CO_2 in 2015 (ref. 2). Yet, a global implementation of such high carbon prices is unlikely to be politically feasible in the short term. Instead, most climate policies enacted so far are technology policies or fragmented and moderate carbon pricing schemes. This paper shows that ambitious climate targets can be kept within reach until 2030 despite a sub-optimal policy mix. With a state-of-the-art energy–economy model we quantify the interactions and unique effects of three major policy components: (1) a carbon price starting at US$7 per tonne of CO_2 in 2015 to incentivize economy-wide mitigation, flanked by (2) support for low-carbon energy technologies to pave the way for future decarbonization, and (3) a moratorium on new coal-fired power plants to limit stranded assets. We find that such a mix limits the efficiency losses compared with the optimal policy, and at the same time lowers distributional impacts. Therefore, we argue that this instrument mix might be a politically more feasible alternative to the optimal policy based on a comprehensive carbon price alone.

To limit the mitigation costs and risks of achieving the 2 °C target, it is essential to start comprehensive climate policy as early as possible[3–7]. Recent studies have shown that pledged reductions are not consistent with cost-efficient emissions pathways reaching the 2 °C target[8,9]. Furthermore, a continuation of climate policy at the current ambition level will not lead to a stabilization of climate change[3,6,10,11], and the delay of more stringent mitigation actions will significantly exacerbate the challenge of reaching long-term climate policy objectives[3–6]. Current policies fail to induce the transformation of the energy system to the extent required by long-term climate targets and lead to further lock-in into carbon-intensive infrastructure. Not only do too much emissions occur in the near term, but also mitigation later on is rendered more difficult[12,13]. It is an important question whether technology policies can reduce such lock-in and mitigate the impacts of delay. Although a few studies based on global energy–economy models have considered single packages of technology policies in their analysis of twenty-first-century mitigation pathways[3,11,14], none of them explored this question.

The environmental economics literature has also not focused on the scope of technology policies for overcoming deficiencies in carbon pricing. In this strand of scholarly work, technology policies have mainly been analysed as means to cure market failures

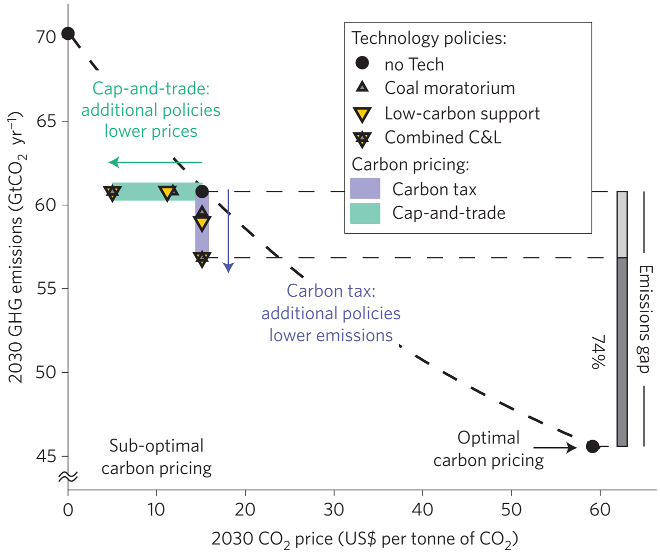

Figure 1 | Relationship between carbon prices and total GHG emissions in 2030. The three filled circles show the scenarios Zero-noT, Cap/Tax-noT and Opt-noT and the dashed line is an exponential fit with asymptotic value of 35 $GtCO_2$. The additional symbols denote the technology policy scenarios with cap-and-trade and carbon tax, as illustrated by the arrows in the graph.

beyond the pure pollution externality, for example, due to learning spillovers, information asymmetries and so on[15–17]. In contrast, here we analyse their complementary role under sub-optimal carbon pricing. There is wide agreement that market-based instruments pricing the externality of emissions have an advantage in terms of efficiency[1]. At the same time it is debated whether or not setting a price (carbon tax) or a quantity of tradable permits (cap-and-trade) is preferable[18–20]. Some authors find that the interaction with other instruments favours the price instrument[20], a finding that our study extends to the case of sub-optimal carbon pricing combined with technology policies.

This study is the first to assess which mix of emission pricing and technology policies is effective in avoiding further lock-in and initiating the transformation required for limiting warming to 2 °C. We thus fill an important gap in the literature by informing the ongoing climate policy debate, which so far revolves around modest approaches to carbon pricing and various forms of technology policies in several countries around the world,

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Table 1 | Description of medium-term policy options considered in the scenarios.

	Name	Scenario	Description
Pricing dimension:	Zero	Zero carbon price	Baseline scenarios with zero carbon price.
	Cap	Sub-optimal carbon pricing implemented as cap-and-trade system	Emission target for 2030: 60.8 $GtCO_2$ globally, in line with extrapolation of lenient interpretation of Copenhagen pledges[4,9].
	Tax	Sub-optimal carbon pricing implemented as carbon tax	Globally uniform carbon tax of US\$7.3 per tonne of CO_2 in 2015, increasing at 5% p.a.
	Opt	Immediate optimal carbon pricing with respect to 2 °C target	CO_2 budget of 1,500 $GtCO_2$ for the period 2000–2100 with full flexibility on when and where emissions occur.
Technology dimension:	noT(ech)	No additional technology policy	Only the pricing determines technology choice.
	CM	Coal moratorium	Ban on construction of new freely emitting coal-based transformation capacities for electricity, liquids, gas and H_2.
	LCS	Low-carbon support	Minimum targets for global installation of different renewable electricity generation capacities (wind power, photovoltaics, concentrated solar power), CCS deployment (gas electricity and bio-liquids) and electric vehicles. Excess costs for solar and wind generation are refinanced through electricity price mark-ups to avoid rebound effects.
	C&L	Combined coal moratorium, low-carbon support, tax and subsidy reform	Combination of coal moratorium and low-carbon support plus an accelerated phase-out of final energy subsidies (until 2030 instead of 2050), plus international convergence of transport fuel taxes.

All monetary values are given in constant 2013 prices. The Methods section and the Supplementary Information contain further details on the scenario design.

tantamount to a lack of comprehensive emissions pricing in line with the 2 °C limit.

Our analysis identifies a policy mix that—based on the positive effects of technology policies under sub-optimal carbon pricing—keeps ambitious climate targets within reach and is possibly easier to implement politically. It does so by addressing two crucial questions: (1) how weaker-than-optimal carbon pricing schemes and additional technology policies interact, and (2) which combination can best reduce the adverse effects of sub-optimal carbon pricing.

To this end, we employ the energy–economy–climate model REMIND (refs 21,22) for analysing a variety of scenarios with combined carbon pricing and technology policies in the initial period of 2015 until 2030, followed by pricing-only policies for the remainder of the century designed to be consistent with the 2 °C climate target. Table 1 provides an overview of the considered policies along the two dimensions pricing and technology, including the definitions of the scenario components Opt, Cap, Tax, Zero, noT, CM, LCS and C&L. To enable a meaningful comparison, the two pricing policies are chosen such that they coincide in the case without additional technology policy and with reference energy demand assumption. The corresponding greenhouse gas (GHG) emissions level of 60.8 $GtCO_2$ in 2030 represents a lenient extrapolation of the Copenhagen pledges[23] and falls short of optimal mitigation action with respect to a 2 °C target in each of the nine models participating in the AMPERE study[4].

In addition to the reference cases without any technology policies, we consider three technology policy packages that imply the continuation and global roll-out of technology support and regulation as observed in a number of countries (Supplementary Fig. 7). The considered policies target developments that have been identified as robust features of transformation pathways in previous studies[24–26], such as a shift towards low-carbon energy supply, a phase-out of carbon-intensive fossil technologies, in particular coal, and an electrification of end-use. To evaluate how well the policy packages prepare the energy system for the long-term requirements of climate stabilization, we then assess the costs and challenges of achieving the 2 °C target with first-best policies from 2035 onwards. During the 2015–2030 period, we assume that the later increase of policy stringency remains unanticipated. We contrast these cases to the (counterfactual) first-best benchmark, which assumes optimal policies starting in 2015.

We find that the combination of weak carbon pricing with technology policies falls short of closing the emissions gap in 2030 (ref. 8), with emissions between 56 and 61 $GtCO_2$ compared with ~45 $GtCO_2$ resulting from the optimal carbon price of close to US\$60 per tonne of CO_2 (Fig. 1). Additional technology policies can result in up to ~4 $GtCO_2$ lower emissions at a given price level (tax regime), or up to ~70% lower prices to reach a given

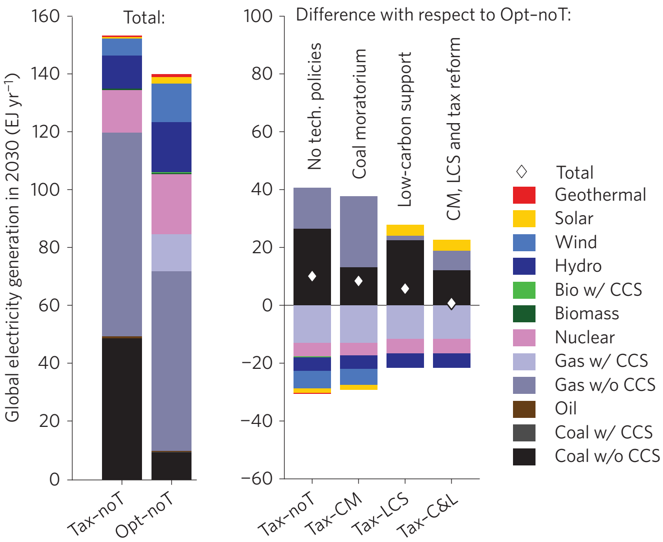

Figure 2 | Global electricity generation by technology. The left panel illustrates absolute numbers in 2030; the right panel shows differences between the benchmark Opt-noT and the different policy scenarios.

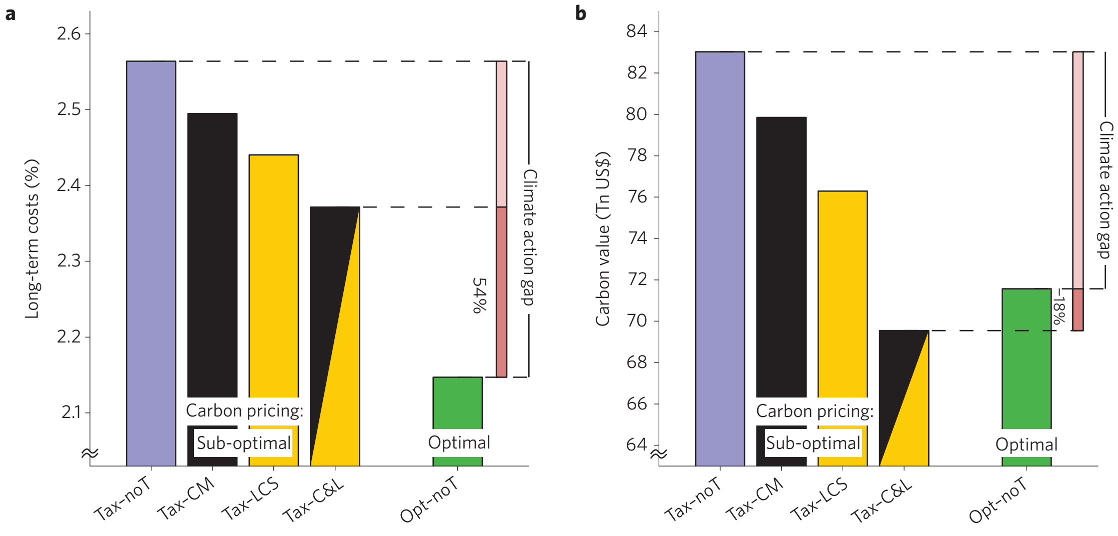

Figure 3 | Economic indicators for the long-term challenges of achieving the 2 °C target after 2030. a, Cumulated discounted consumption loss relative to a baseline without any climate policy from 2010 to 2100. **b**, Cumulated discounted carbon value from 2010 to 2100 (for definition and calculation of these indicators, see ref. 5 and Supplementary Section F).

emissions level (cap regime). This illustrates how ancillary policies break the symmetry between price and quantity instruments[20]. This asymmetry has important implications for the effectiveness of complementary technology policies, and is discussed further below.

In line with previous multi-model studies[24,25], we find that under first-best carbon pricing (Opt–noT), the decarbonization of power supply is already well advanced by 2030 (Fig. 2). Coal is almost completely phased out and low-carbon generation technologies, in particular wind and gas combined with carbon capture and storage (CCS), expand considerably. The right panel shows that the technology policies bring the electricity generation system closer to the optimal configuration, both in terms of total electricity output and technology mix. Nevertheless, in each of the weaker-than-optimal carbon pricing scenarios, freely emitting coal and gas-based power generation is higher and total low-carbon electricity generation is lower than in the benchmark. The additional constraints in the CM, LCS and C&L scenarios in the electricity system lead to higher electricity prices, so total demand and generation decrease. The coal moratorium leads to lower coal prices and thus higher use of coal outside the electricity system, for example, for steel production. This is a case of emissions rebound or inter-sectoral leakage[27] (Supplementary Fig. 3) that reduces the effectiveness of the CM policy. We observe that LCS and CM policies have complementary effects on power sector decarbonization because they act in different directions. Lower coal use does not induce higher use of low-carbon energy as a side effect, and vice versa. Therefore, the combined policy package C&L comes closest to the deployment in the Opt–noT scenario.

The emissions gap[8] or other emission-based indicators of the mitigation challenge[3] do not capture the adverse economic effects of sub-optimal climate policies over the next decades. As more policy-relevant alternatives, we therefore use four indicators of economic mitigation burden employed previously in the literature[5] (Figs 3 and 4), and define the climate action gap as the increase in these indicators in scenarios with sub-optimal policies relative to the first-best optimal policy case. The indicators represent both long-term economic and distributional challenges (long-term costs and carbon value) as well as the specific challenges in the decade after the transition to comprehensive mitigation action (short-term costs and energy price increase) associated with the unanticipated change of climate policy after 2030 (for definition of these indicators, see ref. 5 and Supplementary Section F). Thus, they allow us to judge the political feasibility of keeping the 2 °C target within reach, given a chosen near-term policy mix until 2030.

Our main finding is that additional technology policies help to lower the socio-economic challenges in all four indicators considerably. They partly offset the additional cost arising from sub-optimal carbon pricing: adding the combined technology policy package C&L to the Tax scenario closes roughly half (Fig. 3a and Supplementary Fig. 4a,b) to more than the full gap (Fig. 3b) to the first-best scenario Opt–noT. The effect of the technology policies on the four economic indicators is thus much more pronounced than the effect on 2030 emissions (Fig. 4). It should be emphasized that the positive effects of technology policies are not related to un-internalized externalities as in previous studies[28]. Rather, technology policies partially compensate for the lower-than-optimal carbon price by mandating specific technology developments.

According to all indicators, the LCS policies are more effective than the CM policies. This is due to the fact that, in the LCS scenario, a relatively fast early retirement of coal-based power plants built until 2030 is possible. Although it involves the write-off of invested capital ('stranded assets'), it does not by itself lead to increased energy prices after 2030 and thus has only limited impact on the overall economy. On the other hand, the CM policy does not induce an increase in the deployment of crucial carbon-free technologies, as gas substitutes most of the coal in electricity generation (Fig. 2). Therefore, an extremely rapid ramp-up of carbon-free installations is necessary once comprehensive climate policies are enacted, resulting in sizeable cost mark-ups and stronger energy price increases (Supplementary Fig. 1c). Most importantly, though, the climate action gap analysis confirms the high complementarity of the CM and LCS policies, as in each indicator the C&L policy is more effective than each policy alone.

If technology policies are added to optimal carbon pricing, the economic impacts are mixed (Supplementary Fig. 5). Even though additional technology policies slightly increase long-term costs and energy price hikes, they lower the total carbon value and thus might reduce financial flows and alleviate (international) distributional challenges.

The comparison of scenarios with and without combined technology policies illustrates an often overlooked trade-off between economic efficiency in terms of long-term costs versus distributional impacts and institutional requirements measured in terms of the carbon value. The efficiency losses as measured

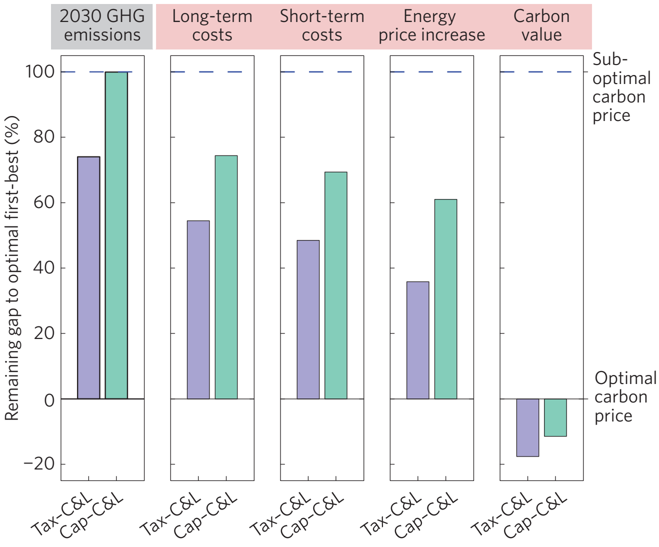

Figure 4 | The effect of technology policies on the emissions gap and the climate action gap. The impact is measured in terms of 2030 emissions, as well as in terms of the four economic indicators presented in Fig. 3. The axes use relative units and are normalized to the gap between the Cap–noT scenario and the optimal first-best scenario Opt–noT. A value of 100% is thus equivalent to 'additional technology policies bring no improvement', and a value of 0% is equivalent to 'the combination of a low carbon price with technology policies achieves the same result as in the optimal policy scenario'. Negative values in the case of the 'carbon value' indicator indicate that this mitigation challenge is lower in the scenarios with technology policies than in the first-best case. The values for the tax scenarios are also depicted in the explanatory 'climate action gap' bar on the right side of each panel of Fig. 3 and Supplementary Fig. 4 and the 'emissions gap' bar in Fig. 1.

in the cost indicators are the price to pay for the lower carbon value and the lower implementation barrier of technology policies reflected in their widespread adoption today. Even in the case of optimal carbon pricing, the additional technology policies do not significantly increase short-term consumption losses compared to a first-best 'carbon pricing only' policy (Supplementary Fig. 1d), highlighting the potential low-regret character of such policies.

The additional technology policies are much more effective in closing the climate action gap when combined with a carbon tax rather than a cap-and-trade system (Fig. 4). The difference is equivalent to about 20% of the climate action gap between the weak pricing and the optimal pricing scenarios without any technology policies. Only for the carbon value indicator, the difference is smaller, as lower carbon prices before 2030 in Cap scenarios partly offset the higher prices post-2030. The reason for the advantage of the carbon tax policy is that carbon prices are not impacted by the technology policies (Fig. 1). Therefore, one of the channels for leakage present under cap-and-trade is absent under a tax, leading to a lower emission rebound and less deployment of carbon-intensive fuels in the near term (Supplementary Figs 2 and 3).

If, in addition to supply-side technology policies and sub-optimal carbon pricing, a dedicated push for energy efficiency is undertaken until 2030, the advantage of the Tax pricing scenarios is even more striking (Supplementary Fig. 6). In the equivalent Cap scenarios with energy efficiency push and technology policies, the carbon price until 2030 drops to zero and thus removes the price incentive for an energy transition.

The results of our analysis suggest that a well-designed technology policy mix complementing moderate carbon pricing might be politically more feasible than the optimal policy of a universally high carbon price, as it entails lower distributional impacts and builds on policies already implemented in several countries. The stylized policies represented in this study leave room for a variety of implementation approaches, enabling policy learning and adaptation to specific circumstances. For instance, a carbon price floor added to a cap-and-trade regime can be an alternative to implementing a carbon tax in its pure form.

In the long term, a global economy-wide carbon price at a high level remains a key necessity for reaching the deep decarbonization required for 2 °C stabilization. In the near term, as shown by our work, complementing a moderate carbon price with technology policies can offer a pragmatic entry point to ambitious climate policy.

Methods

We use the integrated energy–economy–climate model REMIND (refs 21,22) to assess the long-term implications of different short-term climate-related policies. REMIND is an inter-temporal general equilibrium model of the global economy with a technology-rich representation of the energy supply system. It differentiates 11 world regions and runs on 5-year time steps. The model usually operates with perfect foresight over the full modelling time frame 2010–2100. Thus, learning externalities are internalized. Here, we construct two-stage scenarios with sub-optimal policies until 2030, followed by first-best policies that limit global warming to 2 °C. Before 2030, the model does not anticipate the later tightening of emission policies. This leads to an overinvestment into carbon-intensive capital and underinvestment into the scale-up of low-carbon technologies.

REMIND captures crucial aspects of system inertia and path dependencies, as vintage capital stocks of more than 50 energy-conversion technologies as well as technological learning of wind, solar and electro-mobility technologies are represented explicitly. All technologies are subject to cost mark-ups in the case of fast upscaling. Furthermore, the model considers existing final energy taxes and subsidies[29] and the scarcities and constraints driving resource prices.

It has to be stressed that all long-term modelling of the future evolution of the global economy has considerable limitations. The scenarios described in this paper should therefore not be interpreted as predictions, but rather as means for analysing interactions between different policy instruments and energy system developments. Despite the explicit representation of second-best near-term policies, the scenarios still assume idealized conditions in many aspects, for example, optimal saving and investment decisions and full regional cooperation.

Until 2030, two different carbon pricing policies and four different technology policies are combined (Table 1). We define the policies on the global level. Thus, the scenarios establish a benchmark against which national climate policy proposals can be compared. In Cap scenarios, an upper bound on global GHG emissions of 60.8 $GtCO_2$ in 2030 is prescribed; hence, CO_2 prices until 2030 vary depending on the technology policy scenario. In Tax scenarios, in contrast, the tax rate is fixed across scenarios but GHG emissions in 2030 differ (Fig. 1). We chose the tax rate such that without additional technology policies, the Cap and the Tax scenarios are identical. The path of the tax rate starts at US$7.3 in 2015. In both variants, CO_2 prices until 2030 increase by 5% p.a., jump to the optimal level in 2035 and then increase by the endogenous time-variable interest rate in the model of 5–7%.

In the first technology policy option, coal moratorium (CM), no new freely emitting coal-based conversion plants for the production of electricity, liquids and gaseous fuels can be built. To represent the projects under construction, a global total of 150 GW coal-fired electricity plants with technical lifetimes of 35–40 years can be built until 2020. The only freely emitting channel for coal that can be expanded is thus the use of solid coal in industry and for heating purposes.

The second technology option, low-carbon support (LCS), foresees a dedicated push for certain low-carbon options, implemented as a lower bound on their global deployment. For some technologies, such as wind (globally 1.6 TW in 2030), solar photovoltaics (900 GW) and concentrated solar power (18.5 GW) as well as electric light-duty vehicles (27 million vehicles), the implied market developments represent a continuation of market growth observed in the past years (Supplementary Fig. 7). This market growth was the result of policy support such as, for example, feed-in-tariffs. In the model, the extra costs for wind and solar are financed by a premium fee applied to electricity usage. The two additional technologies supported in the LCS scenarios, natural-gas-based electricity generation with CCS and biofuels conversion with CCS are financed out of the general budget. Here, technology policy in the real world has to be ramped up compared with observed policies to foster research, development, demonstration and deployment. The lower bounds in 2030 are 1.4 million barrel oil-equivalent per day for biomass refineries and 50 GW for gas power plants combined with CCS.

The third technology policy variant, coal moratorium and low-carbon support (C&L), is a combination of the other two, with an additional change of final energy taxes and subsidies. Whereas in all other scenarios, final energy taxes stay constant and consumer subsidies are phased out linearly until 2050, C&L scenarios foresee a faster phase-out of subsidies until 2030 and a convergence of transport fuel taxes to a level of ∼US$0.4 l^{-1}.

From 2035 on, comprehensive optimal carbon pricing limits the cumulative 2000–2100 CO_2 budget to 1,500 $GtCO_2$. This implies a 50–60% probability of keeping the increase in global mean temperature in 2100 below 2 °C compared with pre-industrial levels[30]. Other forcing agents are priced equivalently, on the basis of 100-year global warming potential values[4]. Further details on the methods can be found in the Supplementary Information.

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Author contributions

C.B. and G.L. designed the research with input by R.C.P., E.K. and O.E.; C.B. performed the modelling and data analysis; C.B. wrote the paper with contributions and edits by all authors.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to C.B.

Competing financial interests

The authors declare no competing financial interests.