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A two-step carbon pricing scheme enabling a net-zero and net-negative CO_2-emissions world

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Abstract
This contribution introduces a novel carbon pricing system and illustrates its benefits. The system is based on two related but distinct ideas. First, we group the global pools of carbon into three aggregate pools, and we tax or credit human-caused carbon fluxes across the boundaries of the pools. Second, we base the tax or credit solely on physical movements of carbon between pools; hence, the system uses a physical baseline instead of a behavioral baseline based on the hypothetical emissions levels that would have arisen absent the carbon price. The proposed system goes beyond the limitations of current carbon pricing schemes for a number of reasons: it is designed to capture all positive and negative emissions based purely on their climate impact, allowing a broader scope and more appropriate incentives than current systems; it avoids creating bad incentives, particularly those caused by additionality requirements found in carbon offset systems; it captures the complexity of carbon movements through human and natural systems; it reduces measurement errors; and it provides transparent and easily observed price signals. Though this manuscript is conceptual in nature and refrains from discussing the technicalities related to the implementation of the proposed carbon pricing system, we trust that it may contribute to the development of policies enabling a net-zero and net-negative CO_2-emissions world.

Keywords Carbon pricing · Carbon tax · Carbon pools · Net-zero emissions · Negative emissions technologies · Carbon policy

Abbreviations

B	Baseline
BAU	Business-As-Usual
BECCS	Bio-Energy with Carbon Capture and Storage

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C	Carbon
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture Utilization and Storage
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CO_2	Carbon dioxide
DAC	Direct Air Capture
DACCS	Direct Air Capture with Carbon Storage
GHG	Greenhouse Gases
NET	Negative Emission Technologies
PSC	Point-Source Capture

1 Introduction

The pathways required for reaching the Paris Agreement goals of limiting warming to either 1.5°C or 2°C from pre-industrial levels (Paris Agreement 2019) require achieving net-zero CO_2 emissions around 2050 and deploying large-scale negative emissions technologies (NETs) afterwards (Rogelj et al. 2018).

NETs are based on carbon dioxide removal (CDR) technologies coupled with permanent storage, and can be broadly distinguished in: (i) solutions that rely entirely on human-made measures and engineering technologies to remove CO_2 from the atmosphere and put it away, such as Direct Air Capture (DAC) coupled with CO_2 Storage (DACCS); (ii) solutions based on favoring the uptake of CO_2 by natural systems solely, such as afforestation and reforestation, changes in agricultural practices that enhance soil carbon storage, changes in management practices of coastal ecosystems, and enhanced weathering; (iii) mixed solutions that rely on the CO_2 uptake through biomass growth coupled with a human-made intervention, such as Bio-Energy with CO_2 Capture and Storage (BECCS) and bio-char production and storage; and (iv) oceanic options for CO_2 removal and sequestration, such as iron fertilization and ocean alkalinization (Minx et al. 2018; Fuss et al. 2018; National Academies of Sciences, Engineering and Medicine 2019).

Currently, NETs have been incorporated into pricing or other incentive systems piecemeal, primarily through offsets or subsidies for demonstration projects. Current offset systems have raised concerns that existing NETs have led to false claims of emissions reductions (Schneider et al. 2019) and are merely an excuse to continue to use fossil fuels. Moreover, once NETs are deployed on a large scale, offset systems are unlikely to be able to account for complex movements of carbon in human and natural systems.

We propose a novel two-step system for incorporating NETs into a carbon pricing mechanism. The system is based on the movement of carbon between pools, i.e., domains where carbon atoms are stocked as elemental constituents of different chemical compounds. We identify three aggregate carbon pools: (1) carbon in the atmosphere and in the oceans, (2) carbon stored permanently, and (3) carbon held by humans. Taxes and credits would be based on physical carbon fluxes between these pools rather than on changes in emissions relative to hypothetical baseline emissions that would have occurred absent a carbon pricing system. The resulting two-step system is able to cover both positive and negative emissions in complex chains of production, it reduces measurement costs, and it provides a transparent incentive on actors. Overall, the system is designed to account for the complexity of the ways carbon moves in human and natural systems. Moreover, it reduces some of the most difficult, but by no means all of the measurement and fraud problems raised by NETs.

There is a large body of work surveying the potential for different types of NETs and the technological problems that different systems will face (Minx et al. 2018; Fuss et al. 2018; Nemet et al. 2018). There is also a large literature evaluating policy instruments for incentivizing NETs (Bellamy 2018; Honegger and Reiner 2018; Cox and Edwards 2019; Carton et al. 2020). However, we are not aware of any work proposing a system similar to the two-step approach based on physical movements of carbon suggested here. Kortum and Weisbach suggest splitting a carbon tax on emissions into two components, one on the demand side of the market and one on the supply side, but do not incorporate NETs (Kortum and Weisbach 2020). Others have advocated for a portfolio approach, in which carbon taxes are combined with other instruments, e.g., subsidies, mandates, regulated offset markets, etc. (Mehling and Tvinnereim 2018; Rhodes et al. 2021; Tvinnereim and Mehling 2018; Daggash and Dowell 2019; Burke et al. 2019). For example, Daggash and Mac Dowell have proposed to adapt carbon pricing mechanisms to remunerate CDR services as well as to penalize emissions to achieve deep decarbonization of the power sector.

The paper is structured as follows. Section 2 describes the goals of our system and puts them into perspective with problems in current systems. Section 3 introduces, describes, and justifies the two-step carbon pricing system proposed in this work. Section 4 illustrates how the proposed system works through a variety of examples covering different sectors. Finally, Section 5 draws conclusions and presents open issues.

2 Problems with current systems and goals of the study

The design of a carbon pricing system involves a number of interrelated choices including the scope of the system (i.e., which greenhouse gases and which emissions and sinks are priced), the point of taxation, the tax rate or cap, the use of the tax or auction revenue, the interaction with other environmental policies, compliance, administration and measurement issues, reporting and information collection, the international effects and trade concerns, and the distributive effects both within and among countries (Nordhaus 2008; Metcalf and Weisbach 2009; Bordoff and Larsen 2018). We focus on three of these design issues: the scope of the pricing system, the point of taxation, and the baseline against which actions are measured. To simplify the discussion, we assume that the pricing system is implemented as a tax rather than a cap and trade system. A parallel analysis would apply to cap and trade systems.

The *scope* of a carbon pricing system is the set of emissions and sinks that are covered by the system. A broader scope includes more emissions and sinks, with a *complete* system covering all emissions and sinks. The advantage of a broad scope is that its actors see the full social costs and benefits for more of their actions, ensuring that actions that have the same effect on the climate are priced the same way (Hoel and Karp 2001; Newell and Pizer 2003; Wittneben 2009; Coria and Jaraite 2019; Brooks and Keohane 2020). For example, neither wind power nor coal-generated power combined with CO_2 capture result in CO_2 emissions. Both these power generation technologies have the same effect on the climate. These actions should, absent a countervailing reason (such as measurement issues), face the same net tax burden, which a broad scope ensures. A pricing system with a narrow scope, which does not treat these actions equivalently, means that actors may choose one of these solutions when another is more effective or has a lower social cost.

Current systems, including pricing systems in operation and the various carbon pricing bills proposed in the United States, are *incomplete* and have a narrow base, as they do not consider all sources of emissions and sinks, and do not treat all actions that have the same effect on the climate in the same way (Resources for the Future 2021). For example, a significant international effort has been undertaken in the last fifteen years to abate carbon emissions by preserving forests, for example through the UN-REDD (United Nations-Reducing Emissions from Deforestation and forest Degradation) and REDD+ initiatives (United Nations 2020). On the other hand, little effort is currently made to foster CO_2 capture and storage (CCS), although its impact on climate is the same for each ton of carbon permanently sequestered (Deutch 2021).

The *point of taxation/crediting* is the place in the economy where the tax or the credit is levied. A carbon tax on the emissions from fossil fuels can be imposed on the extraction of the fossil fuels, on the combustion of the fossil fuels during production, when the resulting goods or services are consumed, or on a mix of these. The different approaches have been extensively discussed and compared (Mansur 2010; Matthews 2010), and arguments have been made advocating both upstream and downstream approaches (Metcalf and Weisbach 2009; Calder 2015; Metcalf 2017).

The point of taxation can affect the scope of the tax system when there is trade in fossil fuels or in the goods and services created with fossil fuels. Not only would an extraction, production, and consumption base differ when there is trade, but the point of taxation/crediting can have an impact on what is known as carbon leakage. Taxing domestic extraction, for example, might generate different responses in other parts of the world than taxing domestic production because extraction might be less mobile than production (or vice versa) (Kortum and Weisbach 2017).

The point of taxation/crediting can also affect the cost of administering the system (which in turn affects the scope). The European Union Emissions Trading System is imposed on industrial production, which requires a large number of entities to comply with the system. Some current carbon pricing proposals in the United States, however, suggest imposing the tax upstream on the extraction of fossil fuels (or nearly so) along with border adjustments for imports and exports of energy (Durbin 2020). The net effect is to tax emissions from domestic production but with the point of taxation largely on extraction. The reason for doing so is that there are fewer upstream extractors than there are midstream producers, making it easier to administer an upstream tax, and as a result, allowing the scope to be broader.

Finally, all carbon pricing systems must measure actions against a *baseline*, defined as the amount that is subtracted from emissions or sinks to determine the tax or credit, respectively. For emissions, most carbon taxes assume a baseline of no emissions (a "zero" baseline). For example, a fossil fuel-fired power plant might be required to pay a tax for any emissions, or in other words, their emissions minus the zero baseline. Alternatively, the tax could be imposed only on emissions above some specified amount, such as a projected emissions reduction pathway.

In contrast, for sinks, carbon offset systems usually grant credits only for changes from a hypothetical baseline of what the sink would have been absent the availability of the credit, i.e., the credit corresponds to the sink minus that hypothetical amount. To illustrate, consider for example the case of forest preservation. If the baseline scenario is that the forest is destroyed (e.g., it is cut to produce wood that is burned to generate heat and power) (The Guardian 2019; Souza-Rodrigues 2019), forest preservation would receive credits as it results in avoided emissions with respect to the baseline scenario (United Nations 2020).

If instead, the baseline scenario is that the forest remains intact, preserving the forest would not receive any credits as it leads to the same carbon emissions as the baseline scenario.

Current and proposed systems often use inconsistent baselines for emissions and offsets, and the reasons for the different choices are often unclear. This inconsistency can lead to inappropriate results where emissions and offsets are part of the same plan. In addition, baselines based on hypothetical behaviors can create significant measurement problems, known as additionality, as well as bad incentives, as discussed in Section 3.4

In summary, considering the limitations of current pricing schemes mentioned above, our goal is to design a system that satisfies the following criteria:

(1) It should be as complete as possible, consistent with reasonably accurate measurement.
(2) It should be as transparent as possible, and should be purely based on the effect that actions have on the climate.
(3) It should minimize measurement errors and allow relevant actors to observe emissions and sinks.
(4) It should be as simple as possible and as inexpensive as possible in its administration so as to limit its economic burden.
(5) It should effectively cope with trade in fossil fuels and goods produced from fossil fuels, and should be designed to address problems of carbon leakage.
(6) It should rely on a fair, consistent, and adequate baseline, that does not introduce bad incentives.

3 Novel two-step carbon pricing system with physical baseline

To design a system that meets these goals, we rely on two related but distinct ideas. The first idea is that we group the global pools of carbon into three aggregate pools, and we tax or credit movements (carbon fluxes) from one pool to the other. The three aggregate pools are separated by two boundaries, and their crossing generates a tax or credit depending on the direction of the flux. We argue that by adopting this *two-step carbon pricing mechanism*, the system is better able to capture the complexity of the movements of carbon within human and natural systems. The second idea is the introduction of a *physical baseline*. Rather than basing the tax or credit on hypothetical emissions levels that would have arisen absent the tax or credit, we suggest a purely physical measurement based on the movement of carbon between pools.

In the following, we first describe the carbon pools in general, and how they are usually aggregated in conventional carbon pricing systems. Then, we discuss the design of the proposed carbon pricing system, focusing on its advantages over conventional systems.

3.1 Carbon pools and fluxes

Climate change is due to the human-caused redistribution of carbon among carbon pools on the planet. For the sake of simplicity, the following five carbon pools can be identified (Le Quere et al. 2009):

– Atmosphere (containing an estimated amount of about 800 gigaton of carbon, GtC);
– Hydrosphere (about 40,000 GtC);

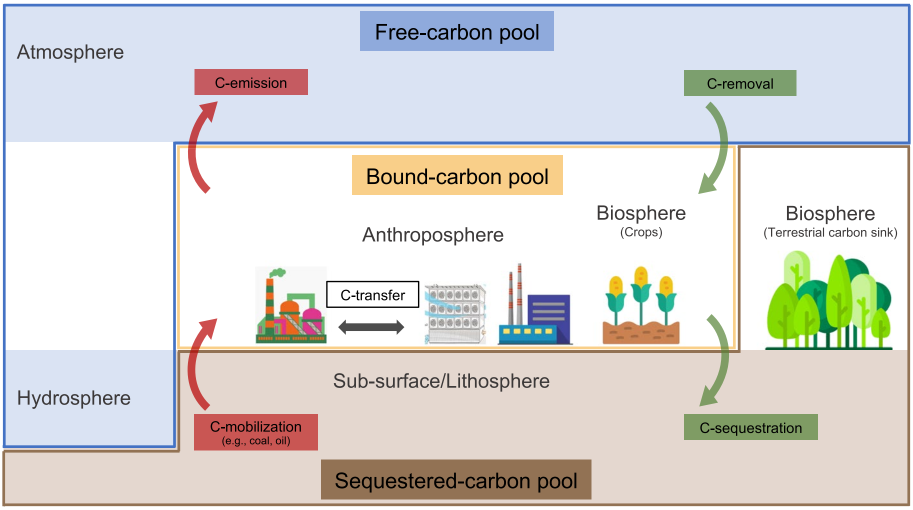

Fig. 1 Schematic of aggregate carbon pools and fluxes

- Biosphere (i.e., vegetation and soil, about 2,500 GtC);
- Lithosphere (i.e., about 65,000,000 GtC, of which about 4,000 GtC consist of fossil fuels);
- Anthroposphere (i.e., carbon stored in manufactured products such as fuels, fertilizers, polymers, estimated to be 2 to 3 GtC).

While natural exchanges of carbon between the first three pools are on the order of 100 GtC/y, anthropogenic greenhouse gas emissions correspond to only about 10 GtC/y (or equivalently about 37 $GtCO_2$/y), but are sufficient to disrupt the pre-industrial carbon balance and to alter carbon concentrations in the atmosphere to such an extent that leads to climate change.

The five carbon pools can be aggregated in various ways to tax carbon emissions and to credit carbon sinks. For the purpose of designing the pricing scheme, we define three aggregate pools as previously introduced in Section 1 (see Fig. 1):

Free-carbon pool (carbon in the atmosphere and in the oceans): This consists of atmosphere and hydrosphere, where carbon is present mainly in a chemically oxidized state (low energy state) in the form of gaseous CO_2 (the only carbon stock exerting a greenhouse effect) or of dissolved CO_2 (as free acid, bicarbonate and carbonate). These two carbon stocks exchange CO_2 freely and tend, though slowly, to a natural equilibrium whereby the increase in one stock is accompanied by the decrease in the other.

Sequestered-carbon pool (carbon stored permanently): This includes the subsurface, i.e., the lithosphere where carbon is present as carbonate minerals (e.g., limestone), as fossil fuels (coal, oil and natural gas) and also as gaseous CO_2, either in natural CO_2 deposits or associated to natural gas. This pool includes also (i) artificial carbon sinks that guarantee permanent carbon sequestration, such as carbonated recycled concrete, and (ii) the terrestrial carbon sink, which consists mostly of forests and soil storing carbon both above and below the ground (Keenan and Williams 2018; Ncipha and Sivakumar 2019). The CO_2 absorbed by plants through photosynthesis is transferred to biomass through growth, and is then passed to soil or released through respiration. The carbon stored as biomass can persist from few seasons to several centuries (e.g., in wood in long-living trees). When plants die, most of the carbon stored as biomass is transferred to soils, where it can be stored for thousands of years more before eventually being re-emitted to the atmosphere (Keenan and Williams 2018). Overall, the terrestrial carbon sink contributes to slowing the rate of global warming by permanently storing CO_2 emissions, and it is influenced by human activities such as afforestation and deforestation. Since crops generally experience a rapid turnover of carbon (e.g., seasonally), they contribute marginally to the terrestrial carbon sink, and they are excluded from the sequestered-carbon pool (Keenan and Williams 2018). The natural transfer of carbon between the sequestered-carbon and the free-carbon pools takes place, not only through CO_2 uptake and release during biomass growth and carbon release upon vegetation decay, but also through volcanism, mineral weathering, and natural forest fires.

Bound-carbon pool (carbon held by humans): This consists mainly of the anthroposphere and includes also the fraction of the terrestrial biosphere used for crops, which contribute to CO_2 removal from the atmosphere but do not act as permanent carbon sinks. Note that the anthroposphere is neither a large carbon stock nor does it offer permanent storage of carbon, essentially because it has a capacity limited by the space available on the Earth's surface to accommodate carbon-bearing manufactured products. Carbon stocked in the bound-carbon pool does not affect the climate as long as it is properly managed and kept there; ultimately, this carbon will have to be either released to the atmosphere or to the hydrosphere (i.e., to the free-carbon pool), or permanently sequestered (i.e., in the sequestered-carbon pool through, for example, geological storage or storage in construction materials).

We identify five categories of carbon fluxes that may occur between the pools described above. They correspond to crossing, in both directions, the interface between sequestered- and bound-carbon pools, and that between bound- and free-carbon pools, and to transferring carbon between agents within the bound-carbon pool (see Fig. 1). Two additional categories could be identified with the movements of carbon directly from the sequestered pool to the free pool, e.g., carbon released through a forest fire, or the reverse, e.g., carbon captured through reforestation. These movements can be accommodated in the system by treating them as combinations of movements from the sequestered pool to the bound pool and from the bound pool to the free pool, or the reverse (see Section 4.3).

Carbon mobilization: Carbon crosses the boundary from the sequestered- to the bound-carbon pool, for example, when fossil fuels are extracted or limestone is mined. The carbon atoms that were permanently separated from the atmosphere are mobilized through human actions and held in a temporary state in the bound-carbon pool, such as in gasoline tanks, natural gas pipelines, or crushed limestone in cement plants.

Carbon emission: Carbon crosses the interface from the bound- to the free-carbon pool in several everyday situations and industrial environments. A typical example is CO_2 produced by the combustion of fossil fuels and then emitted to the atmosphere, e.g., combustion of gasoline in a vehicle, of heating oil in a building, or of coal or natural gas in a power plant. Other examples include CO_2 release by limestone calcination during the production of clinker, consumption of carbonated beverages, or natural gas leaks from damaged gas pipelines.

Carbon removal: Carbon can be actively extracted from the atmosphere and transferred to the bound-carbon pool, thus reducing the carbon stock in the free-carbon pool. This can be accomplished by purposefully growing biomass or by using DAC technologies, which extract CO_2 from ambient air. The captured CO_2 is then stored in the bound-carbon pool, though temporarily.

Carbon sequestration: Carbon can be permanently segregated from the bound carbon pool), and transferred to the sequestered-carbon pool. This can be achieved by injecting CO_2 from the anthroposphere to underground geological structures, such as aquifers or depleted hydrocarbon reservoirs, where it can stay safely for hundreds or thousands of years, as currently practiced at full commercial scale in the North Sea, North America, Australia, and elsewhere (Ringrose et al. 2017; Ringrose 2018). The permanent trapping of CO_2 in building materials or in human-managed forests, e.g., via reforestation or afforestation initiatives, also qualifies as carbon sequestration (possibly as a combined movement from the free to the sequestered pool including both carbon removal and sequestration).

Carbon transfer: Carbon-bearing substances and materials are commonly transferred and traded at a global scale to provide societal services. Examples abound: fuel distribution from the refinery to the consumers, manufacturing using wood , and CO_2 supply for the production of carbonated beverages. In these and in many more cases, carbon does not cross any border between pools, as it is solely transferred within the bound-carbon pool.

Acknowledging the multi-step nature in which carbon moves through human and natural systems, the two-step system assigns a carbon tax (C-tax) to every transfer across boundaries from the sequestered- to the bound-carbon pool (C-mobilization flux), and from the latter to the free-carbon pool (C-emission flux). Likewise, the scheme assigns a carbon credit (C-credit), to every transfer across interfaces from the free- to the bound-carbon pool (C-removal flux), and from the latter to the sequestered carbon-pool (C-sequestration flux). It is worth noting that the C-credit introduced here is conceptually different from a carbon offset credit. The latter makes up for an avoided climate-negative effect, and is based on the concept of CO_2 not emitted with respect to some baseline (see Section 3.4). The former simply rewards climate-positive actions, with respect to a non-behavioral baseline characterized by no carbon fluxes (Kennedy et al. 2015; Mathur and Morris 2017).

As an example, consider natural gas, which is produced by an oil and gas company (C-mobilization), and piped to a large-volume end user (C-transfer), which may use it to generate power; here, the CO_2 by-product is either emitted to the atmosphere (as in most of the cases today, C-emissions) or it is captured; in the latter case, CO_2 might either be transferred to a company that stores it underground (such as Northern Lights, operating a storage hub in the North Sea starting in 2024 (Northern Lights JV DA 2021), leading to C-transfer and C-sequestration fluxes) or delivered to a greenhouse to accelerate its plants' growth (C-transfer and again C-emissions, because plants sooner or later decay and re-emit the carbon stocked up in their biomass). The owner of the greenhouse might also buy the CO_2 from a DAC company that has extracted CO_2 from ambient air (C-removal). From the perspective of the greenhouse owner, there is no difference between using the CO_2 removed from air and that captured upon combustion of natural gas. However, these two alternatives might result in a remarkably different impact on climate, when considering the overall life cycle of the CO_2 from its source to its final disposal: the former (i.e., using CO_2 removed from air) leads to net-zero emissions, whereas the latter (i.e., using fossil CO_2 produced from natural gas combustion) relies on the extraction of fossil fuels, and eventually causes net-positive emissions of fossil carbon.

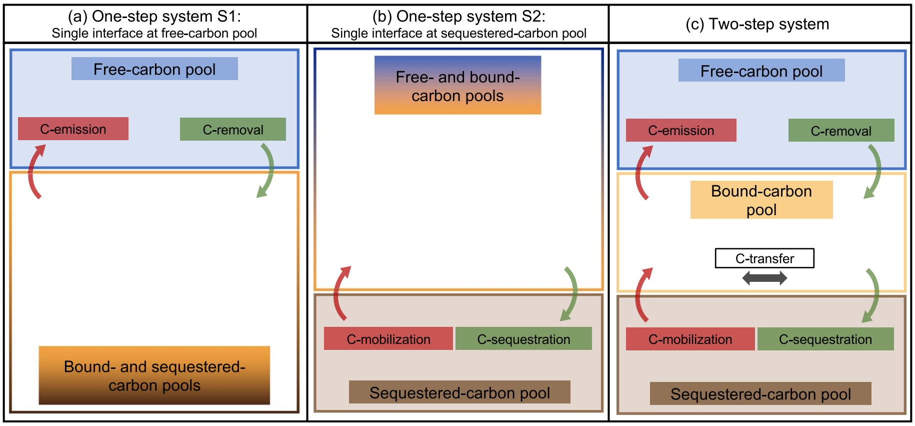

Fig. 2 Schematic of conventional one-step carbon pricing systems with interface at the (**a**) free-carbon pool and (**b**) sequestered carbon pool, and (**c**) of the two-step novel system proposed here

3.2 Conventional one-step carbon pricing systems

Conventional one-step systems rely on two aggregate pools, which can be obtained by further combining the three pools above (see Fig. 2a and b).

The most common carbon pricing system (S1, Fig. 2a) consists of taxing carbon emissions (C-emissions), and is currently adopted by, e.g., the European Union Emission Trading System (ETS) and the California's trading system. This implies aggregating the carbon pools into the free-carbon pool (atmosphere and hydrosphere) and all other pools. Carbon fluxes from other pools into the free-carbon pool cause climate change, hence they are subject to a C-tax. Following the same reasoning, fluxes of carbon, i.e., C-removal, from the free-carbon pool into the other pools, i.e., through CDR technologies, result in carbon credits.

An alternative carbon pricing system (S2, Fig. 2b) could be obtained by aggregating the carbon pools into the sequestered-carbon pool and all other pools. In this case, taxes are levied upon carbon extraction (C-mobilization), and credits are granted upon carbon sequestration (C-sequestration). As extracted fossil fuels are almost all eventually burned, resulting in emissions the extraction tax acts as a surrogate for taxing emissions. Similar considerations apply to credits and carbon sequestration.

3.3 Two-step carbon pricing systems versus one-step systems

The major advantage of a conventional one-step system is its supposed simplicity, as the carbon fluxes need to be measured only across one boundary. In contrast, our two-step carbon pricing system considers the free-, bound-, and sequestered-carbon pools individually, resulting into two boundaries that have to be monitored (see Fig. 2c). Despite this additional layer of complexity, we argue that the advantages of the overall system we propose outweighs the costs of the additional complexity.

3.3.1 Capturing complex movements between carbon pools

Transfers between carbon pools are complex and take place through multiple steps. Such steps consist of actions taken by different actors, separated in space, i.e., they take place in different geographical locations, and in time, possibly months or even years. A two-step system is better able to price this complexity than a one-step system is.

To illustrate why, let us consider DACCS, which removes CO_2 from the atmosphere and sequesters it permanently, e.g., in an underground reservoir. Such transfer involves at least one intermediate storage, e.g., a tank or a ship, where CO_2 is temporarily stored after removal from the atmosphere. Such intermediate storage is typically located close to the earth's surface in the anthroposphere (bound-carbon pool). As such, DACCS is a technology chain comprising at least three steps, corresponding to as many carbon fluxes: Direct Air Capture, CO_2 transport, and CO_2 storage; these fluxes may occur at very different points in time and space, and may well involve different agents and parties.

A conventional one-step system defines a single point in this chain, either when the CO_2 is captured, when it is transported, or when it is stored, to grant a carbon credit. The choice of this point is constrained by other choices in the pricing system. For example, if carbon is taxed when it is mobilized, DACCS will have to receive a credit upon CO_2 permanent sequestration rather than upon CO_2 removal from the atmosphere. Otherwise, capturing, using, and eventually releasing CO_2 into the atmosphere would receive a credit on capture but face no tax on release. The two-step system, instead, would assign a credit for the CO_2 removal from the atmosphere, and either an additional credit in case CO_2 is permanently stored or a tax in case CO_2 is released back into the atmosphere, thus reflecting the actual net impact of the chain on the climate.

Similar considerations can be made for other NETs, as well as for technology chains causing positive emissions, where a C-tax is levied on C-emission and a C-credit is granted on C-removal.

3.3.2 System complexity, avoidance and evasion

Compared to a one-step system, the two-step system broadens the number of participating actors, effectively distributing the costs of carbon taxes and the revenues of carbon credits among different groups. While more actors are taxed or eligible for credits, the incentives for any of them to engage in evasion or to fraudulently claim credits is lower. This is due, on the one hand, to the wider distribution of taxes and credits, hence to their potentially lower values, and, on the other hand, to the adoption of a physical baseline (see Section 3.4). Likewise, the cost to the government of individual acts of evasion or fraudulent claiming is expected to be lower.

Furthermore, the new two-step system we propose is not significantly more complex than current schemes. For emissions, the new system would impose both upstream and downstream taxes. While the latter is currently the most common approach (see for example the European ETS and the California's trading system), it also requires a large number of entities to comply with the system; adding an upstream tax on C-mobilization would not create significant additional implementation costs. This is in line with the considerations reported earlier by Kortum and Weisbach (Kortum and Weisbach 2020).

For carbon removal and sequestration, the new system might increase the complexity of current schemes focused on CDR. However, current schemes: (i) are quite new and still being defined (see for example the letter of intent of the European Commission within the framework of the European Green Deal, which includes carbon removal certification as a key initiative for 2022 European Commission (2021)); (ii) often refer to CDR associated with permanent sequestration (see for example Microsoft's Carbon Removal Program Microsoft (2021)). In this case, the contribution of the new system is two-fold. On the one hand, it simplifies the description of the CDR value chain by clearly separating the removal and the sequestration steps. On the other hand, it simplifies the accounting of carbon removal and sequestration through a physical baseline.

3.3.3 Transparency and reliance on explicit prices

One-step systems that impose an upstream tax on fossil fuels extraction rely on actors responding to the price of carbon embedded in fossil fuels, or in the price of carbon that will eventually be permanently sequestered. For example, a C-tax on extraction raises the price of fossil fuels. Actors seeing a higher price, paying an implicit tax, may shift away from fossil fuels.

Actors, however, may respond differently to explicit prices imposed directly on their actions than to implicit prices. For example, a 100 USD price per unit fossil fuel may appear differently to an actor than a 80 USD/unit price with a tax of 20 USD/unit. This could be because of the salience of the tax (Finkelstein 2009; Chetty et al. 2009), or because regulatory and accounting systems treat explicit taxes differently than other prices. The two-step system causes more actors to see explicit prices, possibly increasing their effectiveness. Note that to the extent we believe implicit prices work, the two-step system does not generate problems.

3.3.4 Trade and tax leakage

A tax imposed on the extraction of fossil fuels in the taxing region may have a different scope than a tax imposed midstream on production or downstream on consumption in that region. The reason is that if fossil fuels are imported or exported, the carbon content of fossil fuels that are extracted domestically is not the same as the carbon emissions from the use of fossil fuels. Similarly, if goods or services produced using fossil fuels are imported or exported, taxing emissions from domestic production is not the same as taxing emissions associated with domestic consumption. Moreover, extraction, production, and consumption may not be equally prone to shifting to regions with no, or low, carbon prices, generating leakage (Kortum and Weisbach 2017).

Kortum and Weisbach found that two-step systems are better suited to solving the leakage problem than one-step systems (Kortum and Weisbach 2020). The reason is that a two-step system that combines a price on extraction and one on production or consumption has more moderate effects on the price of energy seen in other regions than one-step systems. As a result, controlling the price of energy through a two-step system allows the taxing region to minimize responses in other regions, thereby controlling leakage. While their findings do not consider NETs, the core idea carries over to the present context and corroborates the expected effectiveness of our two-step system.

To conclude, we believe that the two-step system has potential to improve the design of carbon pricing systems.

3.3.5 Tax and credit rates

As this work is conceptual in nature, rigorous economic modelling of the optimal rates of the taxes and credits introduced by the two-step carbon pricing scheme goes beyond its scope. Nevertheless, we provide three general considerations concerning tax and credit rates.

First, the sum of the carbon taxes (on C-mobilization and on C-emissions) should equal the sum of the credits (on C-removal and C-sequestration) and both should be equal to the social cost of carbon. This ensures that the total price imposed on emissions equals the marginal harm and the total credits offered on permanent removal equals the marginal benefit.

Second, notwithstanding that their sums must be equal, the individual taxes and credits need not be equal to one another. In particular, the tax on C-emissions need not equal the credit for C-removal, and the tax on C-mobilization need not equal the credit for C-sequestration. If these pairs of prices are not equal, the price of bound carbon will adjust in equilibrium to eliminate any arbitrage possibilities.

Third, optimal relative tax rates and relative credit rates will depend on complex considerations that may vary with the setting. For example, Kortum and Weisbach (Kortum and Weisbach 2020) consider the optimal tax rates on mobilization (which they call extraction) and emissions (which they call either production or consumption) in a setting where one region of the world imposes a carbon tax and the rest of the world is passive. The relative rates are chosen in this setting to account for leakage. In other settings, the relative rates on C-mobilization and C-emissions may be different. Similar considerations apply to the relative crediting rates. Because the tax rates and the two credit rates need not be equal to each other (except that they must sum to the same value), these values can be set independently.

3.4 Physical vs. behavioral baseline

In addition to its two-step feature, the proposed pricing system is based on the idea that any anthropogenic carbon flux should be incentivized or penalized based on its positive or negative climate impact, respectively, in absolute terms and not relative to a hypothetical reference scenario. To this end, we propose using a *physical baseline*, which measures carbon fluxes based purely on the movement of carbon between pools rather than a *behavioral baseline* that is based on hypothetical behaviors that would arise absent the carbon pricing system. The rationale behind this choice is based on the following arguments.

Consider, to start, an incomplete system (such as current one-step systems), which, for example, imposes a tax on emissions above a baseline, but does not offer credits for emissions below the baseline. In this case, the choice of the baseline affects the scope of the system. More specifically, a tax on emissions above a BAU baseline (i.e., a baseline corresponding to the business-as-usual level of emissions) has a different scope than a tax on emissions above a zero baseline. The same holds for credits or offsets: the scope of a forest offset program that only allows credits for sequestration above a chosen baseline depends on the baseline.

Let us consider now the ideal case of complete systems. These impose the same marginal price on emissions regardless of the choice of the baseline, which therefore does not affect the system scope. This holds for both C-taxes and C-credits.

However, even for complete systems, the choice of the baseline has significant effects. First, while the baseline has no effect on the margin, it changes the total amount of tax paid or credits received, since the choice of the baseline is effectively a transfer to or from the actors. Second, the choice of the baseline can affect measurement costs. Behavioral baselines are more difficult (possibly much more difficult) to implement than physical baselines. BAU baselines in particular require estimating and measuring the hypothetical behavior that would arise in the absence of the tax or crediting system. For example, the use of a BAU baseline for carbon offsets has lead to widespread problems, known as additionality, because of the difficulty in measuring behavior in a hypothetical world (Song 2019). Finally, if a baseline depends on choices actors make, actors have incentives to anticipate these taxes or transfers (Kaplow 1986), and these incentives can be counterproductive. In particular, if actors anticipate that the baseline will equal a certain value, *B*, they have an incentive to increase or lower *B* before the enactment of the C-tax or C-credit, respectively. If, for example, the baseline for carbon sequestration credits corresponds to the amount of carbon currently stored in existing forests, actors have an incentive to harvest forests prior to the enactment of the sequestration credits. In this case, C-credits may do more harm than good.

Not all baselines create bad incentives. If the baseline does not depend on behavior, the choices actors make cannot affect the credit they receive or the tax they must pay. This consideration holds true for a zero baseline and for baselines that depend on past physical measurements, such as the amount of carbon stored by a forest in a prior year. In both cases, the baseline is purely determined by physical measurements.

Ideally, baselines should reduce bad anticipation effects (and increase good ones), minimize measurement, and if possible reduce cost. We claim that this can be done via physical baselines, which should be used to the extent possible.

3.4.1 Choice of physical baseline

Whereas several physical baselines are possible, the most prominent are *zero baseline* and *current baseline*. A zero baseline implies that all positive carbon emissions (i.e., C-mobilization or C-emission) are taxed and all negative emissions (i.e., C-removal or C-sequestration) receive a credit. A current baseline implies that all positive and negative variations with respect to a fixed amount are subject to a tax and to a credit, respectively.

Let us consider power plants facing, alternatively, a zero baseline and a current baseline. In both cases, the power plants face the same price on the margin, assuming that the system is complete. With a zero baseline, the power plants would pay additional taxes for increases emissions and lower taxes for reduced emissions, with the marginal price being the tax rate. With a current baseline, the plants would again pay additional taxes for increases in emissions above their current level and receive credits for emission reductions (with the marginal price still being the tax rate). With the zero baseline, however, power plants must pay a tax equal to the tax rate multiplied by their level of emissions, while with a current baseline they do not. This results in better anticipation effects of zero baselines with respect to current baselines, which create incentives to increase emissions prior to the tax taking effect. This behavior is observed, for example, in systems that freely allocate permits to existing fossil fuel-fired power plants. That free allocation baseline creates an incentive to keep fossil fuel-fired power plants operational longer than economically desirable so as to receive an allocation of credits.

Similar considerations hold for negative emissions and natural systems. For instance, given a current baseline for forest carbon sequestration, actors have an incentive to lower the current sequestration so that they can receive more credits once the crediting system is in force. This incentive is distinct from the incentive to falsely understate current sequestration: the incentive is to actually lower the current sequestration by destroying forests prior to enactment, and consequently to get credits for replanting.

These examples show how bad anticipation effects can be reduced by using a zero baseline. Nevertheless, zero baselines increase both tax revenues and costs of credits. For example, granting credits for carbon sequestration in forests would result in large sums being transferred to forest owners (equal to the credit rate multiplied by the amount of carbon sequestered). In such cases, choosing a current baseline could be a more preferable approach.

To exploit the benefits of a zero baseline while reducing the costs for credits granted to natural carbon sinks, we propose to adopt:

- a *zero baseline* for anthropogenic carbon fluxes (i.e., no carbon fluxes occur);
- a *steady-state baseline* of a fixed amount based on a prior year for natural carbon sinks, mainly forests and soils (i.e., steady-state carbon fluxes of natural exchange). Such a baseline refers to the steady-state behavior of such systems, but it is backdated, e.g., it is set at the 2010 emissions level of forests and soils. This allows to minimize both bad incentives and costs.

Overall, this set of physical baselines allows to reduce bad anticipation effects and costs, and to minimize measurement errors. Such baselines are used for both boundaries between the three pools of the two-step carbon pricing system described in Section 3.3.

4 Discussion through examples

In the previous section, we introduced and discussed the novel carbon pricing system and its two key features: the two-step nature and the choice of a physical baseline. In this section, we illustrate how this system can be effectively applied to technology chains, acknowledging their overall net climate impact.

Figure 3 illustrates the pricing scenarios resulting from single technologies (e.g., DAC) and technology chains considered as a whole (e.g., DAC-CCUS). First, we observe that any technology or chain causing more carbon fluxes from the sequestered- to the free-carbon pool than vice versa results in positive carbon emissions, hence has a net-negative climate impact. As a result, it ought to pay more C-taxes than the C-credits received. Conversely, technology or chains resulting in negative carbon emissions, with a net-positive climate impact, generate more fluxes from the free- to the sequestered-carbon pool than vice versa, and receive more C-credit than the taxes they pay. A net-neutral climate impact results from technology chains balancing C-taxed and C-credited fluxes.

Examples of standalone technologies are given by points (a) and (d) in Fig. 3. Carbon fluxes subject to one C-tax (a) may be caused by crude oil or limestone extraction, or by combustion. Similarly, carbon fluxes granted a C-credit (d) could be associated to DAC or permanent CO_2 sequestration in the underground.

Examples of technology chains of interest are discussed below, with a focus on carbon capture, utilization and/or storage (CCUS, CCU and/or CCS).

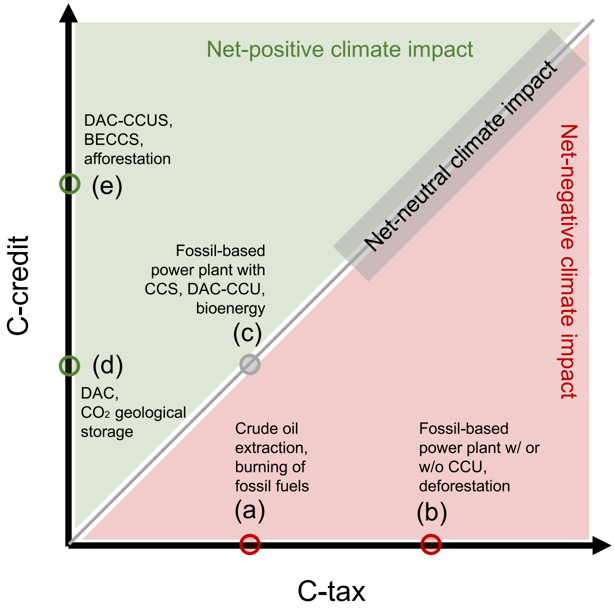

Fig. 3 Carbon pricing system applied to technology chains resulting in net-positive, -negative, or -neutral climate impact

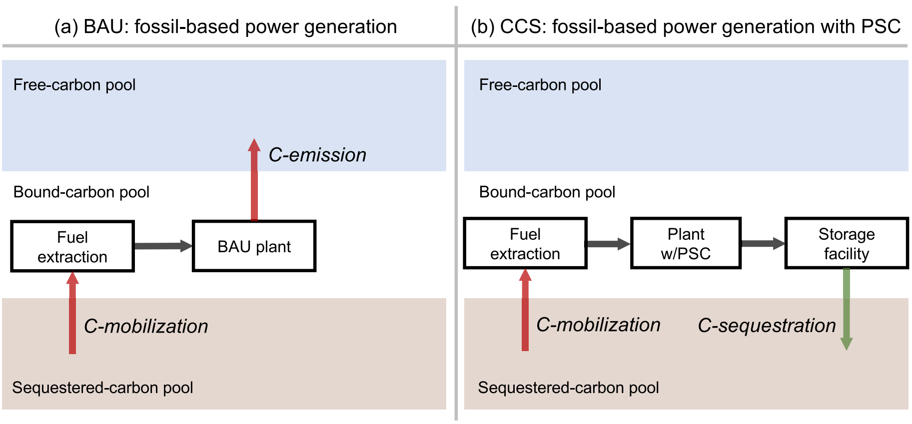

Fig. 4 Illustration of the novel carbon pricing system for power generation for two technology chains, namely (**a**) BAU and (**b**) CCS

4.1 Power generation

BAU fossil-based power generation relies on the extraction of fossil fuels that cause a corresponding amount of CO_2 emissions upon combustion. According to our carbon pricing system (Fig. 2c), the BAU chain results in a C-mobilization and a C-emission flux, hence in two C-taxes computed with reference to the zero physical baseline, and has a net-negative climate impact as illustrated in Fig. 4a. This technology chain and the resulting pricing system correspond to point (b) in Fig. 3.

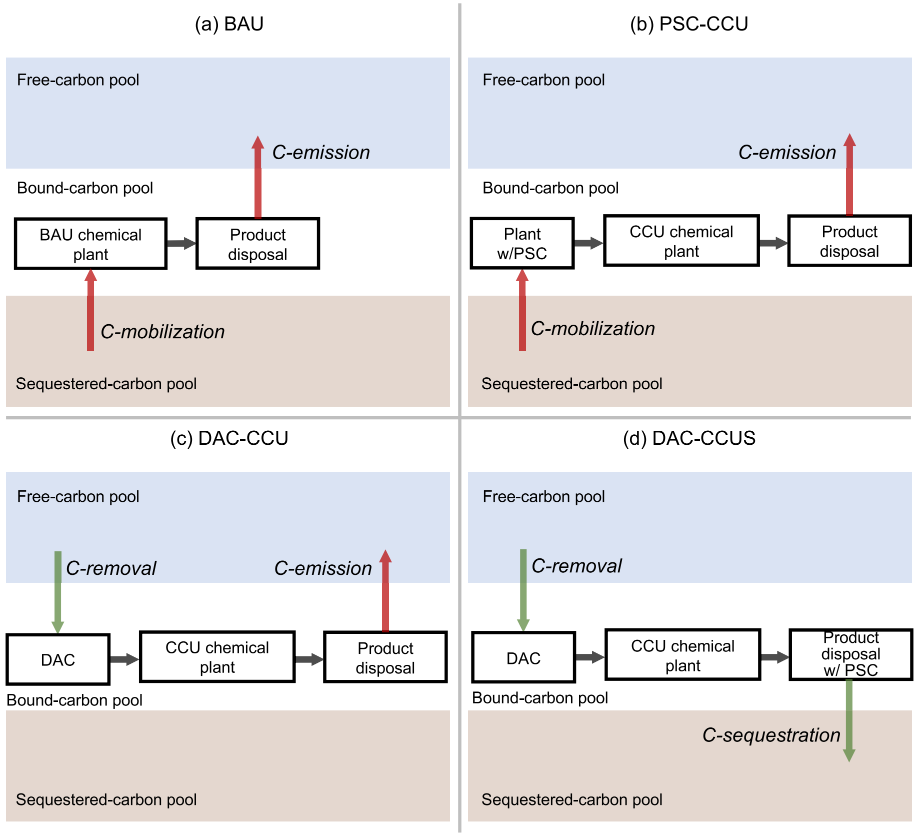

Fig. 5 Illustration of the novel carbon pricing system for chemical industry for four technology chains, namely (**a**) BAU, (**b**) PSC-CCU, (**c**) DAC-CCU, and (**d**) DAC-CCUS

When deploying CCS (Fig. 4b), the CO_2 resulting from the combustion of fossil fuels is captured from the exhaust gases of the power plant via point-source capture (PSC), sent to a temporary storage facility (C-transfer flux), and permanently stored underground (C-sequestration flux). Overall, the CCS chain has a net-neutral climate impact (assuming for the sake of simplicity 100% capture efficiency) and results in one C-tax for C-mobilization and one C-credit for C-sequestration (point (c) in Fig. 3).

4.2 Chemical industry and CCUS technologies

BAU production of carbon-based chemicals relies mostly on two carbon fluxes, one corresponding to C-mobilization of fossil resources, e.g., in the form of crude oil that is used in the production facility, and one corresponding to C-emissions upon product disposal (e.g., incineration), see Fig. 5a (Gabrielli et al. 2020). A C-transfer flux also occurs due to the transfer of the chemical product, e.g., from producer to final consumer, through a specific supply chain. The energy (power or heat) required by the elements of a technology chain, e.g. the conversion of fossil resources into a chemical, results into C-fluxes, hence C-taxes paid by the energy generation plant. The two-step carbon pricing system acknowledges all net-negative climate impacts of chemicals production by levying two C-taxes with reference to the zero physical baseline (point (b) in Fig. 3).

The chemical plant may also use as feedstock fossil CO_2 previously captured from a point-source emitter, thus employing a CCU technology chain (PSC-CCU, Fig. 5b). The resulting C-tax/C-credit balance would remain unchanged with respect to the BAU case. In fact, CCU simply introduces a C-transfer flux within the bound-carbon pool, which is neither taxed nor credited, and possibly delays the C-emissions flux upon product disposal (point (b) in Fig. 3).

A net-neutral climate impact is achieved by employing as feedstock atmospheric CO_2 provided through DAC (DAC-CCU technology chain, Fig. 5c). In this case, the C-tax imposed on the C-emission flux upon product disposal would be balanced by the C-credit obtained for C-removal via DAC (point (c) in Fig. 3).

Finally, if the C-flux resulting from product disposal is captured through PSC and permanently sequestered, i.e., generating a C-sequestration flux (DAC-CCUS technology chain, Fig. 5d), the technology has a net-positive climate impact and would earn two C-credits (point (e) in Fig. 3).

Similar considerations can be made for other CCU technologies aimed at the production of value-added products with limited lifetime, including synthetic fuels (Becattini et al. 2021), fertilizers, or carbonated beverages.

4.3 Biomass

Biomass is deployed across several economic sectors, e.g., food, animal feed and bioenergy, and enables removing CO_2 from the atmosphere and fixing it in a natural fashion. As explained in Section 3.1, plant biomass belongs either to the bound-carbon pool in the case of crops or to the sequestered-carbon pool in the case of the terrestrial carbon sink (e.g., forests). Our pricing system can be applied to regulate human activities affecting plant biomass of both types.

- *Crops*. Biomass crops cultivation pulls CO_2 out of the free-carbon pool and causes a C-removal flux, which should be correspondingly credited. Different pricing configurations can occur depending on the fate of the crops. As crops are not considered permanent natural sinks, such pricing configurations rely on the zero physical baseline. Let us consider the case in which biomass is used for energy production. A C-emission flux is caused upon biomass combustion, and the corresponding C-tax is levied. Overall, this technology chain has a neutral climate impact and the C-tax and C-credit offset each other (point (c) in Fig. 3). If the CO_2 emissions resulting from the biomass combustion are captured and permanently stored underground (C-sequestration flux), i.e., by deploying BECCS, an additional C-credit is earned while no C-tax is levied (point (e) in Fig. 3). This results in the same carbon pricing configuration as DACCS. In case biomass is used for food or feed production, the CO_2 will be naturally re-emitted through human and livestock respiration. In this case, biomass production and consumption are intrinsically connected, and the C-removal credit would be always offset by the C-emission tax with some delay. Therefore, we argue that implementation can be simplified by exempting crops cultivation for food or feed production from the carbon pricing system.
- *Forest management*. Forests contribute to a large fraction of the terrestrial carbon sink and are considered as a permanent carbon storage located inside the anthroposphere, i.e., they belong to the sequestered-carbon pool. Current scientific evidence suggests

that managed and even old-growth forests (of the temperate and boreal zone) sequester carbon at a rate that is relatively independent of the forests' age (namely up to 6 ton of carbon per hectare per annum) (Xu et al. 2014; Rodig et al. 2018; Pugh et al. 2019). Although this implies that, in principle, also mature forests contribute to net carbon removal and permanent sequestration, they are also more vulnerable to disturbances than other components of the sequestered-carbon pool. As a consequence, a proper carbon accounting for forests in the context of carbon pricing methods would require accurate monitoring and continuous refinement of the relevant tools and methods. Being natural carbon sinks, forests are subjected to a steady-state physical baseline (see Section 3.4), which may correspond to a certain carbon flux value (within the threshold of 6 tons per hectare per annum). The carbon taxes and credits discussed below refer to this non-zero baseline. Human activities can affect forests essentially in three different ways, namely through (a) afforestation, (b) deforestation, and (c) forest preservation, which have a positive, negative, and neutral climate impact, respectively.

(a) Afforestation refers to the establishment of a forest in an area where there was no previous tree cover and results in two C-credits: one for removing CO_2 from the atmosphere during the trees growth and one for trapping the CO_2 within the trees in a permanent fashion (point (e) in Fig. 3).
(b) Deforestation implies the removal of a forest from an area that is then converted into a non-forest use and results in one C-tax for carbon mobilization. A second C-tax may also be levied depending on the ultimate use of the obtained timber. This tax would be subjected to the zero physical baseline. For example, if the timber is used for energy production or for the manufacturing of furniture that is eventually disposed of by incineration, a C-tax must be paid for the C-emission flux generated (point (b) in Fig. 3).
(c) Forest preservation implies the conservation of forests (with respect to the steady-state baseline), which in principle has a net-neutral impact on the climate and, therefore, should be neither C-taxed nor C-credited. Nevertheless, in practice, old forests might be poorly managed or exhibit higher susceptibility to disturbances (e.g., fires and storms); therefore, their effective carbon sink potential should be assessed and properly acknowledged through the carbon pricing scheme.

5 Conclusions

This contribution illustrates a novel carbon pricing system (i) consisting of a two-step mechanism based on three carbon pools, where carbon atoms are stocked as constituents of different chemical species (free-, bound-, and sequestered-carbon pools), and of human-caused carbon fluxes across or within the carbon pools boundaries (carbon mobilization, emission, removal, sequestration, and transfer), and (ii) based on the use of physical baselines, in contrast to common behavioral baselines. The proposed system aims at effectively and unequivocally penalizing, through carbon taxes, or incentivizing, through carbon credits, any anthropogenic carbon flux based on its negative or positive climate impact, respectively.

Although this work does not address a number of aspects and technicalities, such as tax and credit rates, the distribution of tax revenues, equity and the distributional effects of the carbon pricing system, carbon fluxes accounting and monitoring, links to existing policy and regulatory frameworks, it focuses on providing a general conceptual framework for effective carbon pricing and on illustrating its benefits. We propose a system that goes beyond the main limitations of current carbon pricing schemes because: (i) it enables the adoption of a broader scope; (ii) it imposes the same monetary value on all behaviors that have the same effect on climate; (iii) it removes any ambiguity concerning the point of taxation and crediting and their coverage; (iv) it accounts for the complexity of the ways that carbon moves through human and natural systems; (v) it minimizes measurement errors; (vi) it enables all actors to observe carbon sources and sinks, and to monitor carbon fluxes between them in a transparent manner; and (vii) it avoids creating bad incentives via carefully defined physical baselines.

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Code Availability Not applicable.

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References

Becattini V, Gabrielli P, Mazzotti M (2021) Role of Carbon Capture, Storage, and Utilization to Enable a Net-Zero-CO_2-Emissions Aviation Sector. Industrial & Engineering Chemistry Research 60(18):6848. https://doi.org/10.1021/acs.iecr.0c05392

Bellamy R (2018) Incentivize negative emissions responsibly. Nature. Energy 3(7):532

Bordoff J, Larsen J (2018) US Carbon Tax Design: Options and Implications. Options and Implications. Tech. rep., Columbia University, New York, US Carbon Tax Design

Burke J, Byrnes R, Fankhauser S (2019) How to price carbon to reach net-zero emissions in the UK. Policy Report, London School of Economics, London

Calder J (2015) Administration of a US carbon tax. In: Implementing a US Carbon Tax: Challenges and Debates (Routledge, New York, 2015), p. 264

Carton W, Asiyanbi A, Beck S, Buck HJ, Lund JF (2020) Negative emissions and the long history of carbon removal. Wiley Interdisciplinary Reviews: Climate Change 11(6):e671
Chetty R, Looney A, Kroft K (2009) Salience and Taxation: Theory and Evidence. American Economic Review 99(4):1145
Coria J, Jaraitė J (2019) Transaction Costs of Upstream Versus Downstream Pricing of CO_2 Emissions. Environmental and Resource Economics 72(4):965. https://doi.org/10.1007/s10640-018-0235-y
Cox E, Edwards NR (2019) Beyond carbon pricing: policy levers for negative emissions technologies. Climate Policy 19(9):1144
Daggash HA, Mac Dowell N (2019) Higher carbon prices on emissions alone will not deliver the Paris Agreement. Joule 3(9):2120
Deutch TE (2021) Energy Innovation and Carbon Dividend Act of 2021. https://www.congress.gov/bill/117th-congress/house-bill/2307/text. Accessed March 2022
Durbin RJ (2020) America's Clean Future Fund Act. https://www.congress.gov/116/crec/2020/08/06/CREC-2020-08-06-pt1-PgS5274.pdf. Accessed March 2022
European Commission (2021) State of the Union 2021 - Letter of Intent. Tech. rep., European Commission, Brussels https://ec.europa.eu/info/sites/default/files/state_of_the_union_2021_letter_of_intent_en.pdf. Available at https://ec.europa.eu/info/sites/default/files/state_of_the_union_2021_letter_of_intent_en.pdf, Accessed on November 2021
Finkelstein A (2009) E-ztax: Tax Salience and Tax Rates. The Quarterly Journal of Economics 124(3):969
Fuss S, Lamb WF, Callaghan MW, Hilaire J, Creutzig F, Amann T, Beringer T, de Oliveira Garcia W, Minx JC (2018) Negative emissions–Part 2: Costs, potentials and side effects. Environmental Research Letters 13(6):063002. https://doi.org/10.1088/1748-9326/aabf9f
Gabrielli P, Gazzani M, Mazzotti M (2020) The Role of Carbon Capture and Utilization, Carbon Capture and Storage, and Biomass to Enable a Net-Zero-CO_2 Emissions Chemical Industry. Industrial & Engineering Chemistry Research 59(15):7033. https://doi.org/10.1021/acs.iecr.9b06579
Hoel M, Karp L (2001) Taxes and quotas for a stock pollutant with multiplicative uncertainty. Journal of Public Economics 82(1):91. https://doi.org/10.1016/S0047-2727(00)00136-5
Honegger M, Reiner D (2018) The political economy of negative emissions technologies: consequences for international policy design. Climate Policy 18(3):306
Kaplow L (1986) An economic analysis of legal transitions. Harvard Law Review 99:509
Keenan T (2018) Williams C (2018) The terrestrial carbon sink. Annual Review of Environment and Resources 43:219
Kennedy K, Obeiter M, Kaufman N (2015) Putting a price on carbon: A handbook for U.S. policymakers. Tech. rep., World Resources Institute, Washington DC
Kortum S, Weisbach DJ (2017) The Design of Border Adjustments for Carbon Prices. National Tax Journal **70**(2), 421. https://doi.org/10.17310/ntj.2017.2.07. http://www.ntanet.org/NTJ/70/2/ntj-v70n02p421-446-design-border-adjustments-carbon-prices.html
Kortum S, Weisbach DA (2020) Optimal Unilateral Carbon Policy. Tech. rep., Energy Policy Institute at the University of Chicago. https://epic.uchicago.edu/research/optimal-unilateral-carbon-policy/
Le Quéré C, Raupach MR, Canadell JG, Marland G, Bopp L, Ciais P, Conway TJ, Doney SC, Feely RA, Foster P, Friedlingstein P, Gurney K, Houghton RA, House JI, Huntingford C, Levy PE, Lomas MR, Majkut J, Metzl N, Ometto JP, Peters GP, Prentice IC, Randerson JT, Running SW, Sarmiento JL, Schuster U, Sitch S, Takahashi T, Viovy N, van der Werf GR, Woodward FI (2009) Trends in the sources and sinks of carbon dioxide. Nature Geoscience 2(12):831. https://doi.org/10.1038/ngeo689
Mansur ET (2010) Upstream versus Downstream Implementation of Climate Policy. Yale University, New Haven, Tech. rep
Mathur A, Morris AC (2017) A U.S. Carbon Tax and the Earned Income Tax Credit: An Analysis of Potential Linkages. Tech. rep., Urban Institute & Brookings Institution, Tax Policy Center
Matthews L (2010) Upstream, downstream: the importance of psychological framing for carbon emission reduction policies. Climate Policy 10(4):477. https://doi.org/10.3763/cpol.2009.0022
Mehling M, Tvinnereim E (2018) Carbon pricing and the 1.5 C target: near-term decarbonisation and the importance of an instrument mix. Carbon & Climate Law Review 12(1):50
Metcalf GE (2017) Implementing a Carbon Tax. Tech. rep, Resources for the future
Metcalf GE, Weisbach DA (2009) Design of a Carbon Tax. Harvard Environmental Law Review 33:499. https://doi.org/10.2139/ssrn.1324854
Microsoft (2021) Carbon Removal Program. https://www.microsoft.com/en-us/corporate-responsibility/sustainability/carbon-removal-program. Accessed March 2022

Minx JC, Lamb WF, Callaghan MW, Fuss S, Hilaire J, Creutzig F, Amann T, Beringer T, de Oliveira Garcia W, Hartmann J, Khanna T, Lenzi D, Luderer G, Nemet GF, Rogelj J, Smith P, Vicente Vicente JL, Wilcox J, del Mar Zamora Dominguez M (2018) Negative emissions Part 1: Research landscape and synthesis. Environmental Research Letters 13(6):063001. https://doi.org/10.1088/1748-9326/aabf9b

National Academies of Sciences, Engineering and Medicine (2019) Negative Emissions Technologies and Reliable Sequestration (National Academies Press, Washington, D.C., 2019). https://doi.org/10.17226/25259

Ncipha XG, Sivakumar V (2019) Natural Carbon Sequestration by Forestry (Springer International Publishing, Cham, 2019), pp. 73–92. https://doi.org/10.1007/978-3-030-29298-0_4

Nemet GF, Callaghan MW, Creutzig F, Fuss S, Hartmann J, Hilaire J, Lamb WF, Minx JC, Rogers S, Smith P (2018) Negative emissions-Part 3: Innovation and upscaling. Environmental Research Letters 13(6):063003. https://doi.org/10.1088/1748-9326/aabff4

Newell RG, Pizer WA (2003) Regulating stock externalities under uncertainty. Journal of Environmental Economics and Management 45(2):416

Nordhaus W (2008) A question of balance: weighing the options on global warming policies (Yale University Press). http://www.jstor.org/stable/j.ctt1npzkh. Accessed March 2022

Northern Lights JV DA (2021) Northern Lights - Accelerating decarbonisation. https://northernlightsccs.com/. Accessed March 2022

Paris Agreement (2019) Adopted Dec. 12, 2015; entered into force Nov. 4, 2016. https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en

Pugh TAM, Lindeskog M, Smith B, Poulter B, Arneth A, Haverd V, Calle L (2019) Role of forest regrowth in global carbon sink dynamics. Proceedings of the National Academy of Sciences 116(10):4382. 10.1073/pnas.1810512116. https://www.pnas.org/content/116/10/4382

Resources for the Future (2021) Carbon Pricing Bill Tracker. https://www.rff.org/publications/data-tools/carbon-pricing-bill-tracker/. Accessed March 2022

Rhodes E, Scott WA, Jaccard M (2021) Designing flexible regulations to mitigate climate change: A cross-country comparative policy analysis. Energy Policy 156:112419

Ringrose PS (2018) The CCS hub in Norway: some insights from 22 years of saline aquifer storage. Energy Procedia 146:166

Ringrose P, Greenberg S, Whittaker S, Nazarian B, Oye V (2017) Building Confidence in CO_2 Storage Using Reference Datasets from Demonstration Projects. Energy Procedia 114:3547

Rödig E, Cuntz M, Rammig A, Fischer R, Taubert F, Huth A (2018) The importance of forest structure for carbon fluxes of the Amazon rainforest. Environmental Research Letters 13(5):054013

Rogelj J, Shindell D, Jiang K, Fifita S, Forster P, Ginzburg V, Handa C, Kheshgi H, Kobayashi S, Kriegler E, Mundaca L, Seferian R, Vilarino M, Calvin K, Edelenbosch O, Emmerling J, Fuss S, Gasser T, Gillet N, He C, Hertwich E, Isaksson LH, Huppmann D, Luderer G, Markandya A, McCollum D, Millar R, Meinshausen M, Popp A, Pereira J, Purohit P, Riahi K, Ribes A, Saunders H, Schadel C, Smith C, Smith P, Trutnevyte E, Xiu Y, Zickfeld K, Zhou W (2018) Chapter 2: Mitigation pathways compatible with 1.5 °C in the context of sustainable development. In: Global Warming of 1.5 °C. An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change (Intergovernmental Panel on Climate Change, 2018). http://pure.iiasa.ac.at/id/eprint/15515/

S.A. Brooks, N.O. Keohane, The Political Economy of Hybrid Approaches to a U.S. Carbon Tax: A Perspective from the Policy World. Review of Environmental Economics and Policy 14(1), 67 (2020). https://doi.org/10.1093/reep/rez022. https://academic.oup.com/reep/article/14/1/67/5681351

SaskPower (2020) Boundary Dam Carbon Capture Project. https://www.saskpower.com/Our-Power-Future/Infrastructure-Projects/Carbon-Capture-and-Storage/Boundary-Dam-Carbon-Capture-Project. Accessed March 2022

Schneider L, Michaelowa A, Brokhoff D, Espelage A, Siemons A (2019) Lessons learned from the first round of applications by carbon-offsetting programs for eligibility under CORSIA. Tech. rep., Öko-Institute e.V., Berlin / Zurich / Seattle. https://www.oeko.de/fileadmin/oekodoc/Lessons-learned-from-CORSIA-applications.pdf. Available at https://www.oeko.de/fileadmin/oekodoc/Lessons-learned-from-CORSIA-applications.pdf. Accessed on December 2021

Song L (2019) Pro Publica. https://features.propublica.org/brazil-carbon-offsets/inconvenient-truth-carbon-credits-dont-work-deforestation-redd-acre-cambodia/. Accessed March 2022

Souza-Rodrigues E (2019) Deforestation in the Amazon: A Unified Framework for Estimation and Policy Analysis. The Review of Economic Studies 86(6):2713. https://doi.org/10.1093/restud/rdy070. https://academic.oup.com/restud/article/86/6/2713/5232206

The Guardian (2019) Deforestation of Brazilian Amazon surges to record high
Tvinnereim E, Mehling M (2018) Carbon pricing and deep decarbonisation. Energy Policy 121:185
United Nations (2020) UN-REDD Programme. https://www.un-redd.org/
Wittneben BB (2009) Exxon is right: Let us re-examine our choice for a cap-and-trade system over a carbon tax. Energy Policy 37(6):2462
Xu B, Yang Y, Li P, Shen H, Fang J (2014) Global patterns of ecosystem carbon flux in forests: A biometric data-based synthesis. Global Biogeochemical Cycles 28(9):962. https://doi.org/10.1002/2013GB004593