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E-ledgers Carbon Accounting

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Abstract. In prior publications, we introduced a global system of interconnected E-ledgers that produces—in as close to real time as practicable—accurate, comparable, and verifiable accounts of the cradle-to-gate (net) greenhouse gas emissions in any product or service that transacts in the economy. In this paper, we delve more deeply into the accounting infrastructure required for the E-ledgers system, including the specific journal entries for recording E-liabilities and E-assets. We explain how the E-ledgers of different entities in the economy articulate with each other and how they connect with jurisdictional E-ledgers that record emissions from end consumers. These entity and jurisdictional E-ledgers can be aggregated into a geological master ledger that tracks anthropogenic GHG emissions and removals, as debits and credits, to a geological carbon equity account. We also provide summary insights from computational technology and pilot studies to guide rapid and cost-effective E-ledgers deployment at scale.

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Keywords: carbon accounting • E-liabilities • E-assets • carbon offsets • carbon markets

1. Introduction

Many entities around the globe are attempting to reduce the greenhouse gas (GHG) emissions from their operations. But the emissions from assets they directly own and operate are typically less than 15% of their total controllable carbon footprint (Cannon et al. 2020). The remainder are incurred by suppliers of their products and services.[1] Only companies with substantial direct energy generation from fossil fuels (using external or internal combustion engines), manufacturers of basic materials such as cement and steel, and operators breeding and raising cattle have direct emissions generally comparable to those incurred by their suppliers. Therefore, entities wanting to drive substantial GHG reductions must have accurate information on the embedded emissions in the inputs they purchase (including energy). These entities, however, face a fundamental problem: they cannot, by themselves, accurately measure the actual emissions incurred by their multiple tiers of geographically dispersed suppliers.

This problem is solvable using a global accounting system of interconnected E-ledgers in which emissions are first measured and validated at their source and then communicated to downstream customers via the specific products and services they purchase (Kaplan and Ramanna 2021). Such a global carbon accounting system is accurate and dynamic, reflecting the actual emissions generated by current production, sourcing, and transportation of products and services. It is also verifiable and comparable across all entities and regions. This paper delves more deeply into the accounting infrastructure required for a global system of E-ledgers. The infrastructure builds upon a foundation of familiar accounting processes, including accounting for inventory; the capitalization and depreciation of purchased property, plant, and equipment; and the cost accounting assignment of purchased materials and conversion costs to output products.

A simple inductive example illustrates how the E-ledgers accounting system works. Consider a company in the middle of a complex supply chain that receives information on the embedded emissions (e.g., kilograms of CO_2) in each unit of input product or service (e.g., kilowatt-hours of electricity) that it purchases from all its direct (tier 1) suppliers. The company also calculates the direct CO_2 emissions from its operations that convert production inputs into output products. The company then follows an internal accounting process to assign the emissions in purchased inputs and from its own operations to output products using causal linkages, akin to activity-based costing allocations of shared resource expenses to output products (Kaplan and Cooper 1998). These steps enable the company to accurately calculate the CO_2 emissions embedded in each output product, which it then reports to each customer purchasing those products. The customer, receiving similar reports from all its other tier 1 suppliers, now has all the information to repeat the process described above to assign purchased and produced emissions to each of its output products, sending that information to each of its customers. This process continues recursively throughout the economy, improving the E-ledgers system's accuracy over time. At three critical steps—recording direct emissions, allocating emissions to products, and transferring emissions from supplier to customer—the transactions are subject to verification by a qualified third-party auditor at the reasonable assurance threshold. This enables the data to be reliable and representationally faithful, even for users many tiers down the value chain.

Other greenhouse gases, such as CH_4, are handled in a similar manner, with companies calculating direct emissions and then allocating all direct and purchased emissions to products using causal logic. Information on different greenhouse gases can travel as parallel channels of accounting data in value chains. This description represents the end state where all substantively significant entities have deployed E-ledgers accounting.

Adoption of E-ledgers, as will be discussed later in the paper, can be initiated either through voluntary application by a handful of companies or through a regulatory mandate. The accounting transactions described in this paper do not change whether adoption is voluntary or mandatory. If launched voluntarily, the long-run sustainability and integrity of the E-ledgers accounting system will likely require regulation and enforcement, as now exists for financial accounting (Ramanna 2025).

Many papers have been published in academic and practitioner journals on corporate environmental, social, and governance (ESG) reporting and its implications for corporate decision making, investment allocations, cost of capital, long-run returns, and societal benefits (see Frankel et al. (2025) for a recent review). Most of that literature is based on voluntary ESG reporting standards, which have been applied in some jurisdictions for companies larger than a specified materiality threshold. Just about all such corporate ESG reporting constitutes "disclosure," not "accounting," because the reporting, and the underlying standards under which it is prepared, fail to meet basic accounting properties such as being representationally faithful, verifiable to a reasonable assurance threshold, fungible, comparable, and mutually exclusive across entities. Because of such structural differences between disclosure and accounting, we are not able to supply antecedents in the ESG reporting literature for the E-ledgers carbon accounting method. E-ledgers carbon accounting was developed to complement existing disclosure approaches, just as disclosure and accounting are complements within financial reporting. To this end, E-ledgers accounting can be used to implement the double materiality reporting requirements that have been prescribed in several regulations such as European Sustainability Reporting Standards. E-ledgers accounting can reveal which entities should report on their carbon emissions because of their materiality, even if they could be exempt from financial reporting because of scale or ownership structure.

The remainder of this paper develops the accounting building blocks needed to implement E-ledgers carbon accounting. Section 2 introduces the three foundational journal entries to record emissions (i.e., E-liabilities) on E-ledgers. Section 3 describes the process for recording consumer and jurisdictional emissions. Section 4 introduces the journal entries when E-assets are created by capturing and sequestering atmospheric CO_2. Section 5 describes how to create a global carbon equity account to track the anthropogenic inflows and outflows of CO_2 between the Earth's geological carbon store and the atmosphere. Section 6 identifies challenges and concerns with adoption and implementation of E-ledgers carbon accounting. These are addressed in subsequent sections. Section 7 shows how a recursive process can start with even a few adopting companies and then, as more entities iteratively supply primary emissions data, converges to a system that produces accurate, dynamic, and verifiable emissions data for all relevant products and services in the global economy. Section 8 describes the potential role of IT-based distributed ledgers and tokens to implement an E-ledgers carbon accounting system at scale. Section 9 illustrates, via an extended case study, how companies can progressively implement the E-ledgers system. Section 10 concludes the paper with suggestions for future academic research on carbon accounting.

2. E-ledger Journal Entries for GHG Emissions

> What advantages does he derive from the system of bookkeeping by double-entry! It is among the finest inventions of the human mind.
>
> (Goethe, translated by Thomas Carlyle, quoted from Ijiri (1993, p. 267))

The E-ledgers carbon accounting system can be operationalized using a double-entry bookkeeping system of journal entries. Three basic journal entries are needed to account for GHG emissions under the E-ledgers approach. Two of them do not arise in financial accounting: they are novel and unique to E-ledgers carbon accounting. The third demands more accuracy and transparency than its financial accounting counterpart.[2]

2.1. Journal Entries for Supplier-Customer Transactions

Consider first the transaction that occurs when a supplier sells and transfers an output product to a customer. In this case, the supplier decreases the E-liability amount in the "Finished Goods" column of its E-ledger by the quantity of CO_2 emissions in the product it has just sold. This is accomplished through a "Dr" (or debit record) entry in the E-ledger. The customer purchasing the product makes a corresponding "Cr" (or credit record) entry in the "Emissions Transferred-in" column of its E-ledger (see Table 1, number 1). In effect, the customer, as part of the negotiation leading to the sale, has willingly assumed the emissions in the product (or service) it purchases. This seemingly straightforward double-entry record for a purchase transaction departs from traditional financial accounting practice by connecting journal entries on ledgers operated by different entities, the seller and the buyer. Such interorganizational journal entries are one of the necessary and novel features of the E-ledgers system of global carbon accounting.

Financial accounting does not use interorganizational journal entries because it produces two fundamental statements, the balance sheet and the income statement. When a company sells a product (crediting its finished goods inventory account), it debits the accumulated cost of the product to an expense account on its income statement. That expense is then subtracted from the revenue the company recognizes from the sale, generating a measure of net income that is independently informative of the company beyond its balance sheet. Carbon accounting, by contrast, requires only a balance sheet or E-ledger because it has no independently informative notion of "income." All emissions are transferred as incurred, analogous in financial accounting to transferring all inventories between entities at cost.

Put differently, the interorganizational journal entries in carbon accounting provide the necessary transparency into the emissions embedded in an entity's purchased products and services. A company preparing a financial income statement and balance sheet does not have to know the operating costs incurred by any of its suppliers, either tier 1 or further upstream, nor does it need to know the prices that its suppliers paid when they purchased products and services from their suppliers. But for carbon accounting, downstream companies need assurance that the emissions information transferred to them is accurate. Interorganizational journal entries provide the mechanism by which downstream entities trace and validate the emissions data reported in their purchased products.

2.2. Journal Entries for Direct Emissions

The second new journal entry occurs when the entity measures and records its direct emissions. The entity records the quantity of CO_2 emissions as an E-liability Cr entry into the "Direct Emissions" column of its E-ledger. This treatment codifies an implicit obligation of the entity (and by extension, of the global economy of which it is part) to the earth. This is the rationale for labeling this entry as an E-liability (Kaplan and Ramanna 2021), with "E" standing for environmental or emissions. Double-entry recordkeeping, however, prompts us to ask the question: "On what ledger should we record the equal and offsetting Dr entry?" The answer is that the Dr entry is made to a geological master ledger, more specifically, to the "equity" account of geological carbon on this master ledger.

The geological carbon equity (GCE) account keeps track of the anthropogenic outflows and inflows of carbon from the earth's geological store to the atmosphere. When, for instance, carbon is released into the atmosphere from the combustion of fossil fuels extracted from the earth, the transaction represents a drawdown (or debit) from the GCE account. Likewise, when CO_2 is released during cement making, as limestone is converted into clinker, the transaction also reflects a debit from the GCE. Conversely, when atmospheric CO_2 is subject to direct air capture and mineralization, the transaction represents an addition (or credit) to the GCE account. Strictly speaking, the geological carbon that is stored in rock and sediments can be distinguished from terrestrial carbon (stored in soil and organic matter) and oceanic carbon (stored in marine bodies). Each of these nonatmospheric stores of carbon can be represented on different equity accounts on the earth's master ledger. In this paper, we simplify by using only a single GCE account to record all anthropogenic outflows and inflows of nonatmospheric carbon.

The offsetting record, therefore, for the entity's direct emission that generated an E-liability credit, is a debit to the GCE account on the geological master ledger (see Table 1, number 2). The two entries recognize (i) a decrease in the geological store of carbon, and (ii) an increase in the entity's (and global economy's) carbon debt to the earth. Section 5 of this paper discusses the candidates who might monitor and maintain this GCE account and the earth's master ledger. Such a geological master ledger is a desirable, but not necessary, feature for adoption of E-ledgers accounting, especially in the early stages of the recursive implementation process described in Section 7.

2.3. Journal Entries for Intraorganizational Allocations

Beyond the two novel interorganizational journal entries in the E-ledgers system, a third type of journal entry records the intraorganization assignment of own-entity and purchased emissions to output products. This allocation process is analogous to the activity-based costing process that accurately assigns factory, general, and administrative expenses to output products to inform management's pricing, product mix, and operations improvement decisions. But external financial reporting does not require accurate costing for individual products. Many companies continue to use simple and arbitrary cost-allocation bases, such as direct labor hours, without triggering any concerns from their external auditors. An auditor is satisfied so long as total expenditures are allocated to production over time and a reasonable split is made between period expenditures allocated to the cost of goods sold in the current period and those capitalized.

Carbon accounting, however, requires an accurate assignment, within a reasonable assurance threshold, of produced and purchased emissions to output products because different customers purchase different output products. If the emissions assignment to output products is biased or inaccurate, the data in the interorganizational journal entry (Section 2.1 above) between supplier and customer will be inaccurate and unacceptable to the customer. Accuracy of the intraorganizational emissions-allocation journal entry is a necessary condition for robustly transmitting emissions information down value chains of indeterminate length and complexity.

The journal entries for allocation of emissions from raw materials (and services) to output products are straightforward when there is a one-to-one link between inputs and outputs. The company debits the relevant E-liability amount from the "Emissions Transferred-in" column of its E-ledger and credits that amount to the

Table 1. This Table Shows E-Ledger Journal Entries for Representative Transactions for a Sample Entity

A. E-ledger of Luca Pacioli Corp.

		E-assets			E-liabilities					
		Removals Purchased & Generated	(E-assets Netted)	NET TOTAL	Emissions Transferred-in	Direct Emissions Generated	Capitalized Emissions	Finished Goods	(E-liabilities Netted)	NET TOTAL
	Beginning balance	0	0	0	0	0	150	10	0	160
1	*Inter-entity transfer of emissions*				*40*					
2	*Direct emissions generated*					*10*				
3	*Allocating purchased emissions to FGs*				*−32*			*32*		
4	*Allocating direct emissions to FGs*					*−10*		*10*		
5	*Capitalizing purchased emissions*				*−8*		*8*			
6	*Depreciating capitalized emissions*						*−12*	*12*		
7	*Sale to end consumers*							*−36*		
8	*Recognizing generated removals*	*18*								
9	*Inter-entity transfer of removals*	*11*								
10	*Netting emissions with removals*		*−13*						*−13*	
11	*Impairment of removals*	*−6*								
12	*Reversing the netting of impaired removals*		*6*						*6*	
	Ending balance	23	−7	16	0	0	146	28	−7	167

Table 1. (Continued)

B. E-ledger of supplier to Luca Pacioli Corp.

		E-assets			E-liabilities					
		Removals Purchased & Generated	(E-assets Netted)	NET TOTAL	Emissions Transferred-in	Direct Emissions Generated	Capitalized Emissions	Finished Goods	(E-liabilities Netted)	NET TOTAL
	Beginning balance	100	0	100	0	0	0	100	0	100
1	*Inter-entity transfer of emissions*							*−40*		
9	*Inter-entity transfer of removals*	*−11*								
	Ending balance	89	0	89	0	0	0	60	0	60

C. Country's consumption E-ledger for end consumer of Luca Pacioli Corp.

		E-assets			E-liabilities		
		Removals Purchased & Generated	(E-assets Netted)	NET TOTAL	Emissions Transferred-in	(E-liabilities Netted)	NET TOTAL
	Beginning balance	0	0	0	10,000	0	10,000
7	*Sale to end consumers*				*36*		
	Ending balance	0	0	0	10,036	0	10,036

D. Geological master E-ledger

		E-assets NET TOTAL	=	E-liabilities NET TOTAL	+	Geological Carbon Equity
	Beginning balance	10,000	=	1,000,000	+	−990,000
2	*Direct emissions generated*					*−10*
8	*Recognizing generated removals*					*18*
11	*Impairment of removals*					*−6*
A	*Change in Luca Pacioli's Net Total*	*16*		*7*		
B	*Change in Supplier to Luca Pacioli's Net Total*	*−11*		*−40*		
C	*Change in Country Consumption Net Total*	*0*		*36*		
	Ending balance	10,005	=	1,000,003	+	−989,998

Notes. The sample entity is shown in panel A: "Luca Pacioli Corp." Certain transactions are intraentity (numbers 3, 4, 5, 6, 10, 12), whereas other transactions are interentity, with Pacioli Corp.'s supplier (panel B, numbers 1 and 9), with its customer who we assumed to be an end consumer (panel C, number 7), and with the geological carbon equity (GCE) account on the geological master ledger (panel D, numbers 2, 8, and 11). Additionally, Panel D shows how the changes in the "net total" E-assets and E-liabilities accounts of various entities and jurisdictions in the economy (e.g., the three representative E-ledgers in our stylized setting) consolidate into the geological master ledger's E-assets and E-liabilities accounts. Panel D also shows how transactions by entities with the GCE account reconcile that account to changes in the geological master ledger's E-assets and E-liabilities accounts so that the fundamental accounting equation "assets = liabilities + equity" is preserved. The values in the table can be considered units of GHG emissions and removals (e.g., kilograms of CO_2) and are entirely fictionalized for illustrative purposes. This table, not intended to be standalone, should be read in parallel with the article's text.

E-ledger's "Finished Goods" column (see Table 1, number 3). Likewise, direct emissions, such as those incurred by an entity through fossil fuel–based energy generation in a plant or in its fleet of vehicles, should be allocated to the entity's range of products using defensible and consistent causal logic. The journal entries in these cases entail a Dr to the relevant E-liability amount from the "Direct Emissions" column of its E-ledger and a Cr of that amount to the E-ledger's "Finished Goods" column (see Table 1, number 4).

When an entity purchases property, plant, and equipment, which will be used across multiple periods, it creates intermediate columns of account in the E-ledger to represent capitalized emissions. For instance, when it determines that the emissions associated with a purchased input should be capitalized, the entity debits the relevant E-liability amount from the "Emissions Transferred-in" column of its E-ledger and credits that amount to the E-ledger's "Capitalized Emissions" column (see Table 1, number 5). Subsequently, in a process analogous to depreciation in financial accounting, the entity allocates a causally defensible and auditor-certified time- or usage-based proportion of the capitalized emissions to its outputs over relevant periods. The journal entries for such "depreciation" entail a Dr of the appropriate mass of emissions from the "Capitalized Emissions" column and a corresponding Cr to the E-ledger's "Finished Goods" column (see Table 1, number 6).

Whereas these intraorganizational journal entries are uncomplicated and familiar to financial accounting practitioners and students, the underlying causal logic that supports these entries is more demanding than for financial accounting allocations. The E-liability Proto-Standard (Ramanna et al. 2024b), produced with inputs from dozens of practitioners and auditors, specifies the principles to which such causal logic must adhere.[3] For instance, causal logic dictates that all emissions embedded in inputs must be allocated to outputs: emissions cannot disappear or be destroyed in the allocation process (analogous to the first law of thermodynamics' energy conservation principle). Causal logic also implies that similar units of output with similar inputs and production processes cannot have different calculated emissions. The converse is also true: different units of output with different inputs and different production processes, run at different times, are unlikely to have the same calculated emissions. Further, causal logic enables the consistent and reasonable allocation of emissions when using a shared input (e.g., a production machine) to produce multiple types of products (or SKUs). Finally, causal logic provides guidance for allocating emissions associated with a common input to various products, such as when crude oil is refined into fuels, lubricants, petrochemical feedstocks, and asphalt.

When the entity sells an output product to another entity, it records a Dr entry to its "Finished Goods" column, and the receiving customer records a Cr entry to its "Emissions Transferred-in" column (a transaction not shown in Table 1 because it just replicates Table 1, number 1's entry).

3. Consumer Emissions and Jurisdictional E-ledgers

The E-ledgers transactions described in Section 2 track the flow of emissions in value chains up to the point of sale to the end consumer. The global carbon accounting system operates by having all entities—businesses, governments, and nonprofits—above a politically determined materiality threshold record, in their E-ledgers, the emissions in products purchased from suppliers, the emissions they produce, and the accurate allocation of purchased and produced emissions to output products.

Some obvious questions are: What happens at and after the point of sale to end consumers? To whom should the embedded emissions in products and services sold to consumers be transferred? And how do we account for the direct emissions generated by consumers? The E-ledgers system does produce reliable cradle-to-gate emissions information, analogous to nutrition labeling, for all products sold to consumers. Consumers can, depending on their values and preferences, use this information to influence their purchasing decisions (Kaplan and Ramanna 2024). The E-ledgers carbon accounting system does not, however, require the earth's eight billion individuals to keep personal E-ledgers. Instead, consumer emissions can be assigned to an E-ledger maintained by the jurisdiction where the consumer makes the purchase or engages in activities that generate direct emissions.

Jurisdictions could be a city, a province, a country, or even a supranational entity such as the European Union. E-ledgers of lower-level jurisdictions can be easily consolidated up to higher-level jurisdictions using standard accounting principles of consolidated reporting across subsidiaries. For illustrative purposes below, we will use a country as a typical jurisdiction. With this definition, when an entity makes a final sale to an end consumer, the E-liabilities of the product or service are debited from the E-ledger of the selling entity and credited onto the jurisdictional E-ledger of the country where that consumer made the purchase (see Table 1, number 7). This E-ledger accounting treatment for consumer purchase and use is inspired by GDP accounting's treatment of consumption as the end state of global value chains. If the consumer product is subsequently recycled and introduced back into the economy, only the incremental emissions from the recycling process are considered part of that product's second-use E-liabilities. This accounting treatment is consistent with the underlying thermodynamics.

Consumers additionally produce direct emissions when they combust fossil fuels to drive their transportation vehicles, heat their homes, and mow their lawns. These emissions are readily recordable on their country's E-ledger. The journal entries are a Cr for the appropriate amount of E-liabilities on the country's E-ledger and a Dr for the equivalent amount to the GCE account. Fossil fuel refiners and retailers can supply to jurisdictions the carbon content and quantities of fuels sold to end consumers, enabling accurate calculation of consumers' direct emissions using simple arithmetic on readily available data.

Outside of fossil fuel use, end consumers do not engage substantially in direct chemical reactions that generate GHG emissions, such as combusting limestone for cement making.[4] Emissions from electricity that individuals use to heat or cool their homes, play video games, or ask questions of generative AI platforms will already be recorded by the utilities producing that electricity. Likewise, transport companies will already be recording the emissions when individuals ride a public bus or fly in a commercial plane. Those emissions are transferred to a country's E-ledger when the consumer buys that service (electricity or transport) in that country.

A jurisdiction (e.g., the government of a country) can maintain a separate E-ledger for the purchased and direct emissions associated with its own activities, such as when it provides safety, defense, public healthcare, and education. This governmental E-ledger, distinct from its consumption E-ledger, can help the jurisdiction make and be accountable for its own decarbonization decisions. The governmental and consumption E-ledgers can be consolidated to create a single jurisdictional (e.g., national) E-ledger for periodic reporting.

4. E-ledger Journal Entries for Removal and Sequestration of Atmospheric CO_2

An E-ledger, as the name suggests, hosts not only journal entries for E-liabilities, the emissions generated and transferred through the economy, but also the journal entries when previously emitted carbon is removed from the atmosphere. Carbon removals, when they meet certain measurement and likelihood criteria, which we describe below, constitute "E-assets." Together, E-assets and E-liabilities are the two sides of an entity's E-ledger.

Carbon removal occurs when atmospheric carbon is captured and sequestered in a nonatmospheric sink such as rock, soil, biological material, or oceans. Different sinks provide different durations of sequestration, with some sinks effectively serving as indefinite stores of carbon, whereas other sinks serve as transient stores for just a few months or years. Given that CO_2 emissions (E-liabilities) are currently expected to last in the atmosphere for somewhere between 300 and 1,000 years (Buis 2019), the duration of a potentially "offsetting" CO_2 removal is a material matter for carbon accounting.[5]

A recent paper proposed five core accounting principles for carbon removals (Kaplan et al. 2023c). The first principle states that a carbon offsetting activity can be recognized as an E-asset only when a specific quantity of CO_2, already generated, is captured and sequestered for a duration comparable to that of existing atmospheric CO_2 remaining in the atmosphere (prudently, 1,000 years). Stated simply, only actual removals qualify as E-assets, not activities that avoid the release of some additional quantity of CO_2 sometime in the future. Such avoidance activities simply result in lower E-liabilities on the ledger of the entity that would otherwise have released the CO_2. This principle may seem obvious from an accounting perspective, but it is necessary to state because the vast majority of today's traded offsets arise from avoidance, not removal activities. The first principle states that avoidance activities cannot create E-assets.

The second principle states that E-assets, unlike E-liabilities, are tradable. E-liabilities are a fundamental informational property of a good or service, and they can be removed from an entity's E-ledger only when that good or service is itself transferred from that entity's financial ledger (e.g., upon an arm's-length sale). By contrast, E-assets, which are nonduplicable property claims to carbon removals, are tradable. This is because the entities that efficiently generate E-assets may not be the ones that wish to use them to offset their E-liabilities, and the trading of E-assets enables buyers and sellers to create economic and environmental value. This principle is a simple application of Ricardian theory of comparative advantage.

The third principle establishes that a removal activity can be recognized as an E-asset only when the duration and magnitude of the removal are both reasonably estimable and probable (similar to traditional asset recognition principles in financial accounting). When both conditions have been met, the journal entry is a Dr to the removing entity's E-ledger (creating the E-asset) and a Cr entry to the earth's GCE account, reflecting an increase in the geological store of carbon[6] (see Table 1, number 8[7]).

A removing entity has the option to trade its E-asset position (per principle 2) with another entity that wants to reduce its net E-ledger position. Thus, E-asset recognition (per principle 3) is also contingent on satisfying, to the reasonable assurance threshold, the asset alienability criterion—that is, if separating an E-asset from its originating entity would inherently impair that E-asset, then that asset should not be recognized. The E-asset sale transaction is recorded as a Cr entry for the E-asset in the selling entity's E-ledger and a corresponding Dr entry for the E-asset in the purchasing entity's E-ledger (see Table 1, number 9[8]).

Principle 4 establishes the condition under which an entity with E-assets recorded on its E-ledger can use those E-assets to offset, "net" out, an equivalent value of its E-liabilities.[9] The condition, simply stated, is that the quantity of CO_2 represented by the E-asset must actually have been removed from the atmosphere and indefinitely sequestered. This condition is analogous to (and based on) traditional financial accounting's "earned" criterion for revenue recognition. (In traditional financial accounting, revenue is recognized when it is earned and when it is realized or realizable. The latter condition is already embedded in the E-asset recognition criterion described in principle 3). The higher standard for netting an E-asset, a requirement equivalent to revenue recognition's earned criterion, is to ensure that the act of offsetting or extinguishing a 1,000-year E-liability does not forerun the actual delivery of the underlying effort to this end. Conversely, the lower standard for E-asset recognition, in advance of full delivery of an indefinite-life removal, is to encourage tradability (and thus financing) of removal offsets.

When an E-asset meets the netability criterion, the journal entries to recognize the offset to an existing E-liability are as follows: first, a contra asset to the E-asset is created, called "E-assets netted," and a contraliability to the corresponding E-liability is similarly created, called "E-liabilities netted." Then, a Cr is made to the contra asset for the relevant offset amount, and a Dr is made to the contra liability (see Table 1, number 10). Upon consolidating this contra liability with the gross E-liability amount, the entity establishes the (now lower) baseline E-liability amount that it needs to then assign to its outputs, which is to be subsequently transferred to customers of those outputs. Naturally, the lower E-liability amount makes its outputs more desirable to carbon-conscious customers, promoting a verifiable market for decarbonization. We note that no causal logic exists for assigning a nettable E-asset to the E-liability of output products. Companies can assign the nettable amount to products sold to customers with the strongest preferences for low emissions in their purchases, consistent with profit-maximizing incentives.

The establishment of the contra asset and contra liability enables the E-ledger to preserve the gross amount of E-asset and E-liability, which is useful for accountability purposes and necessary to enable a previously netted E-liability to be reversed because of an impairment of the underlying E-asset (e.g., if a forest fire prompts rerelease of captured atmospheric CO_2). These impairment events are the focus of the final and fifth principle for accounting for carbon removals.

Because the sequestration of carbon removed from the atmosphere must persist indefinitely, the fifth principle establishes the need for ongoing independent monitoring to determine whether some or all of previously sequestered CO_2 has leaked back into the atmosphere. This monitoring, particularly for certain oceanic and biological carbon sinks, may also detect an accretion, defined as an unexpected increase in the quantity of CO_2 that has been captured and sequestered. Estimating these decrements and accretions of sequestered emissions is a new requirement from E-ledger accounting. Initially, it may be challenging to achieve a reasonable assurance standard for these measurements. We expect, however, that their importance will spur measurement and assurance innovations to allow active markets for carbon offsets to develop and scale.

In case of verified accretion of captured carbon, the journal entries are simple: the E-asset can be debited to reflect the higher amount captured, and the earth's GCE account can similarly be credited. In the case of impairment of captured carbon, two sets of journal entries must be made on the entity's E-ledger, as follows: first, the E-asset must be credited by the impaired amount and the earth's GCE must be likewise debited, reflecting the decrease in the geological store of carbon because of CO_2 rerelease; second, in case the E-asset has already been netted against E-liabilities, the contra asset and contra liability accounts, called "E-assets netted" and "E-liabilities netted," respectively, must be debited and credited as appropriate, reflecting the fact the amount that can be considered netted is now lower (see Table 1, numbers 11 and 12). Importantly, this accounting treatment clarifies that it is the netting entity and not its customers who might have already benefited from buying from that entity a product represented as lower E-liability, who must bear the risk of an impairment event. The treatment is analogous to how equivalent events are handled in financial accounting, and it incentivizes the prudential netting of E-liabilities by an entity.

The notion of an E-ledger that recognizes carbon sinks as E-assets raises the question of what to do about historical "natural capital" assets such as ancient rainforests and peat bogs. Some jurisdictions find themselves, through accidents of history or careful environmental management, stewards of considerable reservoirs of such natural carbon sinks. Under a global E-ledgers system, such sinks can be recognized as E-assets. The benefit from capitalizing them on a jurisdictional E-ledger is transparency and the associated incentive to be careful stewards of this E-asset, to prevent its degradation or impairment, such as through deforestation. But such E-assets cannot be sold as offsets against recently generated and future emissions, as the historical natural carbon sinks already reflect sequestration of (natural) emissions from the distant past. Any such sales will entail double counting. This feature may not be received enthusiastically by those trying to monetize such longstanding carbon sinks.[10] That said, any *additional* accretion of emissions by such carbon sinks (e.g., because of newly managed forest growth) can be recognized as E-assets to be traded (assuming they meet the other principles described above). In such cases, the journal entries would be to Dr the E-asset on the relevant government's E-ledger, with the offsetting Cr entry made to the earth's GCE account.

The E-assets Proto-Standard (Ramanna et al. 2026a) provides further detail on accounting for E-assets.

5. The Earth's GCE account and Its Connection to a Global Consolidated E-ledger

E-ledgers carbon accounting includes "the earth" as a transacting entity in the carbon accounting system. This is intuitive, as E-ledgers are created to track anthropogenic GHG emissions and removals through value chains. The earth—specifically the earth's geological store of carbon—is the principal counterparty for man-made emissions and removals, the journal entries discussed in previous sections. Whereas the GCE could also track natural emissions and removals, such as those from volcanic activity or ocean absorption, these are not necessary for the E-ledgers system to serve its main objective of recording the changes in the earth's geological store of carbon because of human activity. If, therefore, the equity, as of a given date, of the anthropogenic GCE account is negative, this does not imply that the earth as a whole itself is in a negative position on geological carbon (which is physically impossible). Rather, it implies that the impact of anthropogenic activities on the earth's geological store of carbon has been negative, as of that date.

The GCE account is a "trueing-up" equity account on a geological master E-ledger that consolidates all arm's-length businesses, government, and nonprofit entities' E-ledgers and all arm's-length jurisdictional consumption E-ledgers. All anthropogenic direct emissions and removals appear once and only once across all the system's E-ledgers. Thus, the individual arm's-length E-ledgers can be aggregated, following standard accounting rules for consolidation, and the total shown on the E-assets side of the geological master ledger will equal the total shown on the E-liabilities side plus the GCE account balance (see Table 1, panel D). This feature of the E-ledgers system preserves the fundamental accounting equation, assets = liabilities + equity, providing a check on the system to identify instances of incomplete accounting, whether because of negligence, error, fraud, or lack of capacity.

Who or which institution should maintain the GCE account and the geological master ledger? A purpose-built international organization can be established to this end, with members selected from related fields such as accounting, climate science, data science, and statistics. This international organization can draw from existing collaborations across central banks worldwide, including from OECD countries and so-called Global South countries. Central banks, relatively independent of retail politics, have expertise in data acquisition and collection from diverse sources, complex statistical modeling, data analysis, and macroeconomic bookkeeping, which will all be relevant to maintaining the GCE account and geological master ledger. The Bank of International Settlements, sometimes referred to as the global "central bank for central banks," could serve as an incubator for the purpose-built international organization that maintains the geological master ledger and continually updates the GCE account.

A second policy question is how to initialize or calibrate the GCE account. If this account is to represent the impact of anthropogenic activities on the earth's geological store of carbon, must we go back to the dawn of human civilization and backfill records for this account to function? Whereas doing so can improve the system's accuracy, the tracing of anthropogenic emissions and removals back to the origin of human civilization or even to the beginning of industrialization is not critical for the E-ledgers system to accomplish its objectives going forward.[11] Because the GCE account will require a start date, a practical option would be a relatively recent date, such as 2024, when the Paris Agreement's reporting framework came into effect, or one in the near future, such as when a critical number of economies agrees to use the E-ledgers approach. Ignoring anthropogenic net emissions prior to the start date can also be justified by the current scientific understanding that "no substantial further CO_2-induced warming or cooling of the climate system will occur as long as" anthropogenic net emissions *going forward* are reduced to zero (Allen et al. 2025).

Ultimately, neither the choice of the institution to maintain the GCE account nor its initialization date affects the journal entries for E-ledgers carbon accounting, the focus of this paper. The choices on these policy questions can be left to social and political processes. Moreover, as a practical matter, the E-ledgers system can be deployed at the level of individual commercial entities without a formal GCE account. In such a setup, when an entity directly releases or removes GHG from the atmosphere, its recordkeeping is single entry, with the emitting entity recognizing an increase in its E-liability or E-asset balance, making E-ledgers accounting as simple as recordkeeping in a checkbook. Such a single-entry setup would allow for the initiation of E-ledgers accounting in supply chains where it is most material, even as international negotiations occur on the form and governance of the GCE account. This phased, pragmatic approach could facilitate eventual establishment of a GCE account that otherwise might evoke resistance from some activists, entities, and jurisdictions.

6. Challenges and Concerns with E-ledgers Implementation

The E-ledgers carbon accounting system, although simple to explain, must respond to several significant implementation questions if it is to become a global standard. The system relies on all entities with materially significant purchased and produced emissions assigning those emissions to the output products sold to customers. How does the system operate if many entities do not participate during a transitional period to more general adoption or even in the long run because they operate in jurisdictions that have chosen not to participate in a global E-ledger ecosystem? A different version of this question is whether the E-ledgers system can start as a voluntary system, with limited adoption by a few entities at different stages of global supply chains, and recursively scale to a mandated global system. A second concern is how a downstream entity receives assurance about the accuracy of the emissions information in the products it purchases from tier 1 suppliers, especially if most of the direct emissions occur not at a tier 1 supplier but at those two or more tiers upstream. A third question is whether E-ledgers can operate when different jurisdictions follow somewhat different carbon accounting standards, such as exists today for financial accounting where different countries follow U.S. GAAP, International Financial Reporting Standards (IFRS), or local generally accepted accounting principles. A fourth question is the feasibility of doing E-ledgers carbon accounting at the individual entity level. How can a company, nonprofit, or governmental entity, large or small, build the capabilities needed to participate meaningfully in a global E-ledgers system? We respond in part to these implementation challenges and concerns in the paper's remaining sections, also highlighting opportunities for future research.

7. Recursive E-ledgers Adoption

Global adoption of the E-ledgers system cannot occur in a single stage. Pilot projects have shown the complexities of getting even tier 1 suppliers to participate in the E-ledgers process. But implementing the E-ledgers algorithm recursively enables the system to be adopted over time (Ramanna et al. 2024a). Recursion is a computational process in which a seemingly unsolvable problem becomes solvable by breaking it down into iterations. In carbon accounting, the apparent "wicked problem"[12] is calculating accurate product-level emissions data on a dynamic basis for all products that transact and cycle through the global economy. This problem can be solved recursively, through multiple iterations, as described below, in a process similar to how recursion was deployed in the post–World War 2 period to scale bottom-up microeconomic data to an integrated global system of reasonably accurate GDP accounts.

In the first iteration, a small handful of key companies start using E-ledgers, perhaps because of a government reporting mandate, such as the introduction of emissions-based tariffs as now being considered in Europe, or even as part of a voluntary collaborative. Voluntary adoption will be most likely among companies that believe they have a competitive advantage in producing products with lower embedded carbon emissions, those with environmentally sensitive customers and shareholders, and those under environmental scrutiny by external parties. The early adopters can follow the implementation process, described in Section 9, to rigorously quantify the most material parts of their direct and purchased emissions. In this initial stage, companies ideally use their own and tier 1 suppliers' primary data, but when primary data are not available, they draw upon existing and public data, such as from Argonne National Laboratory's GREET database. A combination of these primary and secondary data, together with the accounting processes described in this paper, allows early-adopting companies to generate a first-pass approximate calculation of their product-level emissions. The data from this stage are more accurate than existing product-level emissions data obtained from industry-level estimates but are far from the accuracy required for reasonable assurance audits.

In the second iteration, the emissions calculations from the first iteration are used as inputs into emissions calculations by those entities that are customers of the iteration 1 companies. Given the circular nature of supply chains, some of these customers will be suppliers (tier 1 to tier n) of the iteration 1 companies. By using slightly more accurate input data, the product-level calculations for all companies involved in iteration 2 are now more accurate than in iteration 1.

This process continues over further iterations until all material products and services in the economy have accurate, dynamic emissions. A recent study (von Kalckreuth 2024) used macroeconomic input-output analysis (Leontief 1970) to simulate such a recursion process for carbon accounting. It started by assuming each company had accurate information on its direct emissions but used industry-level emissions estimates for its purchased products and services. Subsequent iterations used tier 1 suppliers' more accurate estimates from the previous iteration. The study found that reasonable assurance levels of accuracy could be achieved in as few as five iterations, assuming geometric growth in company coverage. The recursive process would be turbocharged if policymakers follow the recommendations in the E-liability Proto-Standard to impose a progressively increasing penalty (say, over five years) for companies that continue to use secondary instead of primary data when calculating their product-level emissions (Ramanna et al. 2024b).

8. Implementing E-ledgers at Scale: The Potential Role for Distributed Ledgers and Tokens

The E-ledger approach's principles for asset and liability recognition, charge-offs, and transfers are based on financial accounting principles familiar to today's millions of trained accountants and auditors. E-ledgers accounting, however, is distinctive for its interentity transactions, both when direct emissions and removals are recognized and when inventories are transferred down a value chain. This situation poses a practical challenge: how to ensure secure and verifiable communication, at reasonable cost, of the true and fair emissions embedded in any entity's output products to all downstream users of those products (over multiple tiers). Because many suppliers consider the identity of their suppliers as confidential information, the system should also protect the privacy of suppliers more than one tier away from each company in a global supply chain. Even a few years ago, the compliance costs of implementing a system to accomplish these objectives could have made the E-ledgers approach impractical.

Take the example of a manufacturer of lithium-ion batteries for electric vehicles. The battery contains a multitude of elements, including lithium, cobalt, nickel, manganese, graphite, aluminum, copper, and iron. Each element could be purchased from multiple suppliers, with each supplier having its own deep supply chains involving different country locations, extraction and refining machinery, energy sources, and downstream transportation methods. Each step of that supply chain involves direct emissions and the allocation of input emissions to products. When the battery manufacturer receives information from its tier 1 suppliers on the embedded emissions of its purchases, it must be able to trust that those numbers are "representationally faithful" (in the accounting sense of that term) all the way up the value chain. Some proposals, such as from the European Union, have recommended that companies, like the battery manufacturer, obtain a line of sight, at a qualitative level, into the full richness of the production methods and emissions-accounting decisions of all its multiple-tier suppliers. Such an approach, however, would be costly, cumbersome, and potentially invasive of the trade secrets of companies in the supply chain.

Recent advances in blockchain and distributed ledger technology offer one option for transferring representationally faithful emissions information down value chains (Ramanna et al. 2026b). Using this technology, direct emissions, when recognized on an E-ledger, would be tokenized into indestructible atomistic units of digital "currency" that are then indelibly linked to relevant units of inventory. For example, if two tons of CO_2 emissions are produced by mining one ton of copper at a given facility on a given day, those two tons of CO_2 emissions would be tokenized into, say, two billion emissions tokens (the unit of digital emissions currency) that are now forever linked to that ton of copper. Then, as that copper makes its way down a value chain and becomes embedded into thousands of different products (based on various product-allocation decisions by entities along the value chain), the proportionate amount of tokens (proportionate to the copper) also becomes embedded into the E-liability calculations of those products. The tokens' metadata, at any point in the value chain, contain information such as the date and place where the original token was created, the various E-ledgers through which the token has passed up to that point, and the auditors who have assured the token's transactions across and within E-ledgers, including assurance of all the input-to-output product-allocation decisions.

As the token itself is fungible with the tokens associated with all other products and services moving down a value chain, E-ledgers calculations using tokens are simple. If the token metadata appear in order with all the appropriate and expected audit checks, the user of the token at any point in the value chain can be assured of its true and fair representation of embedded emissions without needing line of sight into the underlying production methods and emissions-accounting decisions of all associated upstream E-ledgers. The token-based technology also preserves the trade secrets of the intermediate entities in the supply chain. In effect, blockchain and distributed ledger technology offer simple, private, secure, and practical deployment of the E-ledgers system.

Two challenges remain for widespread implementation of token-based technology. First, the technology must be interoperable across multiple token suppliers from different jurisdictions and over time. Second, using this technology, which itself can be energy intensive, must not generate more emissions than are saved through entities' informed decarbonization decisions. Policymakers and the technology suppliers will need to assess and address these challenges before tokenization can be applied to implement E-ledgers accounting at scale. And of course, tokenization is only one technology option to consider. Current and future innovations in information technology may also provide the security, verifiability, privacy, and interoperability required for widespread adoption of E-ledgers carbon accounting.

9. Implementation Lessons from Pilot Projects

Since E-ledgers were first introduced in 2021, entities in both high-income and developing countries have implemented elements of the system in pilot projects.[13] These entities include businesses, governments, and nonprofits, and they cover various sectors such as agriculture, mining, manufacturing, and services. We illustrate the implementation process with the first pilot project, performed at GT Tire (GT) in Indonesia in 2022 (Kaplan et al. 2022). GT is one of the world's largest tire companies, with annual revenues of USD $2.5 billion and clients in more than 130 countries as of 2022.

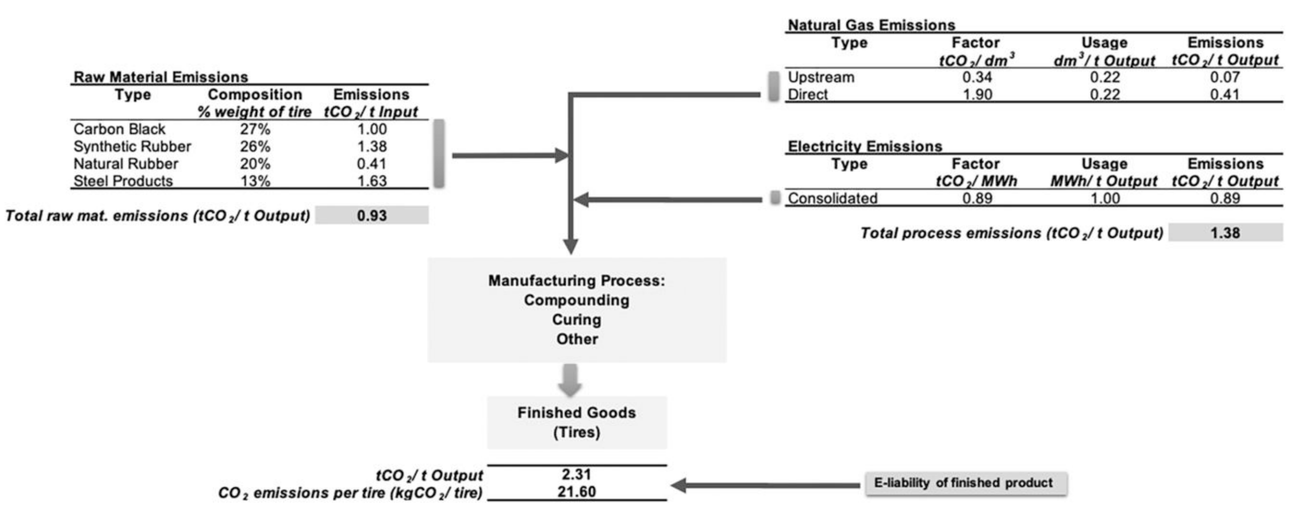
Senior management launched the project by selecting the company's director of quality assurance to be the project leader. He formed a project team with relevant expertise—supply chain, environmental, and IT—and ready access to data critical for the project. The team focused on calculating the E-liability of a standard passenger tire, a product that represented 30% of the Indonesia plant's production capacity. The tire had more than 200 raw materials suppliers. To get started, the team decided to focus on four of the tire's key materials—synthetic rubber, natural rubber, carbon black, and steel, representing about 86% of the tire's weight. The team contacted and gained the cooperation of several of these key materials' suppliers, particularly those already feeling pressure from other customers to quantify and reduce the specific carbon content of their products.

The GT project team obtained granular information from its participating suppliers on the emissions embedded in the particular materials it was purchasing from them. Detailed knowledge of both the price and the associated emissions of each of these input materials would allow GT to optimize across these two dimensions in its purchasing and product-design decisions. In cases where the GT project team did not have access to primary data on materials purchased, the team used public emissions factors, typically from Environmental Product Declarations.

The GT team also collected primary data on some of the emissions produced during its manufacturing processes. The team homed in on the two most energy-intensive processes: heat energy used to mix materials in the compounding process and the energy used during tire curing, when it applied pressure and heat to form the tire. The team allocated the emissions in the purchased materials and in its self-generated and purchased energy to the output product, calculating both the tons of CO_2 emissions per ton of tire output and the kilograms of CO_2 emissions per passenger tire (see Figure 1). The project team took less than two months to reach this stage because much of the necessary data already existed in various (albeit dispersed) formats.

The exercise above enabled the project team to identify opportunities for reducing the tire's carbon footprint by working closer with suppliers and through purchase and production of cleaner energy. The GT project team queried its suppliers about whether and how they could reduce the carbon content in the products sold to the tire company. Several already had their own decarbonization projects underway and were pleased to learn that GT had become an interested customer. A large carbon black supplier suggested that GT purchase products from its new circular production process, which they claimed reduced emissions by 38%. The natural rubber supplier suggested sourcing from a higher productivity plantation, which could reduce emissions by 27%. The steel supplier suggested switching from steel produced with virgin iron ore, processed through basic oxygen furnaces, to recycled steel processed by electric-arc furnaces, a claimed 43% emissions reduction opportunity. Within its own operations, the team estimated double-digit savings by using on-site solar power to replace fossil fuel–based electricity purchased from the grid. Replacing existing boilers with new, energy-efficient gas boilers would also reduce direct emissions by 6%. Bringing all these opportunities together, the

Figure 1. First-Iteration Calculated Emissions for a Standard Passenger Car Tire, GT Pilot Project



Source: GT pilot project team.
Note: Numbers disguised for company confidentiality.

team calculated it could produce standard passenger tires with 22% lower carbon content. The emissions savings would, however, increase the price per tire by about 30% at current demand levels.

The GT project team shared these findings with a large customer, a European OEM of luxury vehicles. The European OEM saw an opportunity to credibly offer lower-emission tires on its luxury brands, where end customers are less price sensitive. But it wanted to learn the emissions in the specific tires it purchased, which were made not in GT Indonesia but at GT's factory in China. This led to another project to assign the emissions produced at the Chinese plant and by its multiple large Chinese suppliers to the tires purchased by the European OEM. This second phase of the GT pilot expanded the scope of raw materials covered from 86% to 95% of the tire's weight.

An important finding, starting with the GT pilot and now replicated at several other pilots in multiple industries and geographies, is that calculating accurate product-level emissions is not as burdensome as first imagined, even for smaller companies. Direct emissions from internal chemical processes can be imputed by using basic stoichiometry and knowledge, from inventory records, of the quantities of input materials used and output products produced by the chemical processes.

The intraorganizational assignment of direct and purchased products' embedded emissions to an entity's output products is also readily accomplished by the following steps: (i) The pilot entity identifies the range of products generated by the facility in question and then identifies emissions-intensive raw materials and direct processes to allocate to those products, (ii) the pilot entity determines the usage of those inputs and production processes in generating each unit of the selected outputs, and (iii) the pilot entity calculates emissions per unit of usage for the selected production processes. This is generally based on dynamic, facility-level direct emissions measurement. For example, the emissions attributable to energy used on site to power production machinery are calculated by multiplying the minutes required by that machinery to produce a unit of output by the emissions per minute of the machine's energy source. The emissions from waste or scrapped materials and from production downtime are also readily allocated to outputs produced, consistent with accounting principles of full allocation.

Much of the information to estimate the emissions in output products already exists in modern companies' information systems. For example, ERP systems capture the quantity of input materials required to produce each unit of output, including the expected waste and scrap in the conversion process. ERP systems should also have the estimated quantity of time required on each machine type to convert input materials into outputs. Auditors can use these ERP data to verify, to a reasonable assurance level, the intraorganizational estimated assignments of direct and purchased emissions to output products.

A common barrier encountered during pilot projects is when important tier 1 suppliers are unable or unwilling to provide dynamic, batch-level data for the products (or electricity) they supply to the pilot entity. Some piloting companies collaborated with reluctant suppliers to build their requisite carbon-accounting capacity (Ramanna and Holloway 2025). Others, such as GT, bypassed the problem by limiting the pilot scope to a handful of key emissions-intensive suppliers that were able and willing to cooperate. Still others, rather than allow gaps in supplier information, reverted to emissions factors as starting values in the pilot process, counting on the recursive adoption path for E-ledgers implementation (described in Section 7) to include more suppliers in future iterations.

10. Conclusion and Opportunities for Future Research

As E-ledgers carbon accounting becomes more widely deployed in entities around the globe, many opportunities are likely to arise for academic research. Business scholars can start by studying how companies, informed by accurate product-level financial and environmental costs, modify decisions about product design, purchasing, logistics, operations, marketing, and sales, as they attempt to optimize across both financial and environmental dimensions. Accounting, economics, and finance scholars have studied the design and impact of incentives for more than half a century. They can use those insights to study how incentives from various stakeholder groups influence the speed and scale of E-ledgers adoption and convergence to a global system of comparable, representationally faithful, and verifiable accounting for carbon emissions. Management accounting scholars can examine how purchased and site- and entity-level emissions can be causally assigned to output products, including the intertemporal allocations of emissions from capital equipment and end-of-life decommissioning. Governance scholars can examine how today's institutional environment around financial accounting—including auditor independence, regulatory oversight, and reputational and legal penalties—can be adapted to facilitate decision-useful and reliable E-ledgers carbon accounting. Such research could include how to develop assurance standards and enforcement that transcend national and regional borders, as exists now for financial reporting. Research can also explore the role for emissions factors drawn from higher percentiles of a product's emission distribution when the product is purchased from noncomplying entities, nations, and regions (as suggested in the E-liability Proto-Standard).

Capital markets researchers can study how the introduction of E-ledgers carbon accounting influences market activity, such as investment, risk taking, capital structure, cost of capital, long-run returns, and relational contracting with directors, employees, suppliers, customers, and regulators.

Additionally, the formal standard-setting for E-ledgers accounting and auditing, similar to what occurs in financial reporting, will be subject to ideological pressures and corporate lobbying. Such pressure can be even more intense should E-ledgers carbon accounting be adopted for taxation and regulation of cross-border trade and investment. Such policymaking should stimulate a vibrant institutional literature on the political economy of E-ledgers legislation, regulation, implementation, and enforcement.

E-ledgers carbon accounting integrates decades of inventory and cost accounting best practices with contemporary developments in information technology. It offers a simple, dynamic approach for accurately calculating emissions embedded in all goods and services that transact in the economy to a standard that is representationally faithful and reasonably assureable. The system can incentivize companies to competitively differentiate their products based on their emissions content, particularly those currently viewed as undifferentiated commodities. Such competition can unleash market-based forces to decarbonize global supply chains or, as we can now say, reverse recent declines in the geological carbon equity account.

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Endnotes

[1] Emissions incurred downstream are usually not "controllable" by an entity (in the accounting sense of the word) because companies in a market economy do not generally dictate how and how much their products shall be used, postsale, by their customers, their customers' customers, and so on (Kaplan and Ramanna 2024).

[2] After publication of Kaplan and Ramanna (2021), several papers described approaches to recordkeeping in carbon accounting (e.g., Penman 2024, Reichelstein 2024). These articles do not feature the fundamental distinctiveness of E-ledgers accounting, the focus of this paper.

[3] The Proto-Standard also specifies accounting principles for measuring and calculating direct emissions, for transferring emissions in and out of E-ledgers, and for the materiality and verification thresholds for such transactions. The Proto-Standard, although not a definitive rulebook, provides guidelines, grounded in accounting and economic theory, for formal carbon accounting rulemaking.

[4] Some consumers may raise cattle for private use, but the scale of such activities is negligible from a geological perspective, so it can be ignored for E-ledgering purposes.

[5] The duration that CO_2 is expected to linger in the atmosphere itself depends on the amount of CO_2 in the atmosphere and thus on anthropogenic efforts to manage CO_2.

[6] As before, for expositional simplicity, we use "geological" here to refer to all anthropogenic removals of atmospheric CO_2 to nonatmospheric sinks, whereas in practice, this common GCE account can be disaggregated into separate geological equity accounts for rock, soil, oceanic, and forest sinks.

[7] For simplicity, we assume in this transaction that the company in panel A (Pacioli Corp.), which will eventually net the carbon removals against its E-liabilities (in transaction number 10), is also generating removals. In practice, entities performing and selling removals are likely to be specialized suppliers.

[8] To avoid proliferation of entities in Table 1, we assume that a single supplier in panel B provides the company in panel A (Pacioli Corp.) with both raw materials and carbon removals. This could occur if the supplier were a petroleum company selling both fossil fuels and direct-air-capture products. In general, however, entities performing and selling removals are likely to be different from those supplying input materials and services to the entity's production processes.

[9] This transaction is feasible because E-assets and E-liabilities are measured in common units, for example, kilograms of CO_2.

[10] Indeed, such a practice has already been attempted (e.g., Andreoni and Brito 2025).

[11] The sunk cost principle also supports a recommendation to ignore past emissions for the GCE account.

[12] A "wicked problem" is a complex, multifaceted social or cultural issue that is difficult, perhaps impossible, to solve because of incomplete information, conflicting values, and interconnectedness.

[13] Details on the pilot projects and the pilot playbook they followed to implement E-ledgers accounting can be found at https://e-ledgers.institute/pilot-adoption/ (see also Kaplan et al. 2023a, b; Ramanna and Kirk 2023).

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