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Monitoring, reporting and verifying emissions in the climate economy

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The monitoring, reporting and verification (MRV) of greenhouse-gas emissions is the cornerstone of carbon pricing and management mechanisms. Here we consider peer-reviewed articles and 'grey literature' related to existing MRV requirements and their costs. A substantial part of the literature is the regulatory texts of the 15 most important carbon pricing and management mechanisms currently implemented. Based on a comparison of key criteria such as the scope, cost, uncertainty and flexibility of procedures, we conclude that conventional wisdom on MRV is not often promoted in existing carbon pricing mechanisms. Quantification of emissions uncertainty and incentives to reduce this uncertainty are usually only partially applied, if at all. Further, the time and resources spent on small sources of emissions would be expected to be limited. Although provisions aiming at an effort proportionate to the amount of emissions at stake — 'materiality' — are widespread, they are largely outweighed by economies of scale: in all schemes, MRV costs per tonne are primarily driven by the size of the source.

Our assessment of the greenhouse-gas emissions MRV — as practised in the climate economy — is based on the material produced for an upcoming book on the same topic[1]. 'Climate economy' is here extended to any incentive for a set of economic stakeholders to reduce their greenhouse-gas (GHG) emissions. The incentive is often a hard economic one (for example a carbon tax), but it can take softer forms, such as reputational incentives attached to meeting an emissions reduction pledge for a country, local government or a company, or branding incentives derived from environmental labelling (for example carbon footprint of products). This scope corresponds to what Ascui and Lovell[2] refer to as the 'market-enabling' frame for carbon accounting, although this largely overlaps with the 'political frame' when jurisdictions such as countries or cities are the object of the carbon pricing and/or management mechanism (CPM).

Fifteen schemes are reviewed here (Table 1). In the tables and figures, project-scale CPMs are grouped or duplicated by type (for example N_2O emissions in agriculture), which is why the number of categories does not always add up to 15. The selection criteria were primarily designed to cover the most important existing CPMs. The importance of each scheme was assessed in terms of number of entities concerned, amount of emissions concerned, longevity of the scheme, and amount of money at stake. Priority was given to compliance schemes: that is, schemes designed by a regulator who issues clear and mandatory guidelines and who has some means of enforcing the guidelines. This unique set of guidelines allows us to state what the existing MRV requirements are, rather than describing how some entities proceed in terms of MRV within a flurry of different approaches. Within the schemes of lesser importance, priority was given to those that presented an original feature (for example the inclusion of the waste sector in the Australian carbon pricing mechanism). Forty-one systematic questions were asked for each scheme (see Supplementary Information), and the relevant literature (peer-reviewed articles, reports, regulatory texts, regulatory impact assessment and so on) was reviewed to help provide answers.

Definitions

'Monitoring' covers the scientific part of the MRV process. It involves getting a number for each variable part of the equation that results in the emissions estimate. This ranges from direct measurement of gas concentration using gas meters to the recording of proxies such as fuel consumption based on the bills of a given entity. The use of proxies is common practice, through the general equation:

$$\text{activity data} \times \text{emission factor} = \text{GHG emissions}$$

where activity data are the proxy (for example fuel consumption, heads of cattle) and emission factor is the conversion factor (tonnes of CO_2 per litre of burnt fuel, tonnes of CO_2-equivalent per animal per year). Both activity data and emission factor change over time and hence need to be monitored. Activity data nevertheless tend to vary more frequently than emission factors.

'Reporting' covers the administrative part of the process. It involves aggregating and recording the numbers, explaining how you came up with them in the requested format, and communicating the results to the relevant authority, such as the regulator or the top management of the company.

The purpose of 'verification' is to detect errors resulting from either innocent mistakes or fraudulent reporting. It is usually conducted by a party not involved in monitoring and reporting, who checks that these two steps were conducted in compliance with the relevant guidelines.

MRV scale

Although not plentiful, the existing literature on MRV in climate economics agrees on three possible scales that greatly influence how MRV can be conducted: jurisdiction, entity and project[3–5].

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Table 1 | MRV costs across CPMs.

MRV scale	CPM or group of CPMs	Standard or regulation	Cost per entity (€ yr^{-1})	Cost per emission (€ per tCO_2e)	Share of verification in total MRV costs	Original sources
Jurisdiction	National inventories	United Nations Framework Convention on Climate Change (UNFCCC)	800,000	0.02	22%	1,28–30
	Subnational inventories (Group of 3 CPMs)	Global Protocol for Community-Scale Greenhouse Gas Emissions (GPC); Covenant of Mayors (Cm); Bilan Carbone Territorial (BCT)	18,500	0.003	0%	31
	Jurisdictional REDD+	Verified Carbon Standard (VCS)	145,000	0.40	24%	32–40
Entity	EU ETS	Monitoring and Reporting Regulation (MRR), Verification Regulation (VR)	22,000	0.07	40%	25,26,41–47
	Landfills in the Australian CPM	National Greenhouse and Energy Reporting Act (NGER)	4,862 (M&R only)	0.22	64%	48–50
	Imported electricity in the Californian ETS	MRR	73,000	0.14	Not available	51–54
	Shenzhen ETS	Specification with guidance for quantification and reporting of the organization's GHG emissions (SZDB/Z 69)	No data	No data	No data	
	Company-level footprint (group of 3 CPMs)	French Grenelle II law Article 75; French Grenelle II law Article 225; Carbon Disclosure Project (CDP)	77,000[a]	No data	No data	55
Project	Offset projects (CDM, all sectors)	Clean Development Mechanism (CDM)	55,000	0.57	32%	32,34,36,37, 39,56,57
	Agricultural N_2O projects (group of 4 CPMs)	Climate Action Reserve (CAR); VCS; American Carbon Registry (ACR); Joint Implementation (JI), France	No data	No data	No data	
	Reforestation projects	CDM	17,000	0.80	48%	33,58–62
	Forest management projects	VCS	Likely to be similar to CDM reforestation projects	Likely to be similar to CDM reforestation projects	Likely to be similar to CDM reforestation projects	
	Fugitive emissions projects	CDM	167,000	0.22	15%	1

For details on acronyms, please refer to Supplementary Table S1. The costs presented are averages of sometimes very wide ranges, most often obtained from company surveys or calculations by the regulator in the impact assessment of its regulation. See Ref. 1 for details on the methods for each carbon pricing mechanism. [a]Includes the costs of all MRV frameworks used by the surveyed UK quoted companies which in some cases report under the CDP, the EU ETS and the CRC at the same time. tCO_2e, tonne of CO_2-equivalent.

The 'jurisdictional scale' includes all emissions occurring within a given geographical area such as a country or an administrative region. All activities and entities operating within the area are considered. Examples include national GHG inventories supervised by the United Nations; regions or cities that have committed to a voluntary or statutory cap on emissions; and jurisdictions engaged in a programme for reducing emissions from deforestation, forest degradation and other changes in forest carbon stocks (REDD+). Although the last example is restricted to forest-related emissions, it still includes all those occurring within the jurisdiction, no matter the activity or entity responsible for them.

The 'entity scale' includes emissions related to the operations of a given public or private entity. In a few cases, all the emissions of the entity are included, such as businesses participating in the Carbon Disclosure Project or entities mandatorily reporting their emissions under the 'Grenelle II' French environmental law enacted in 2010. Most often however, only the emissions corresponding to a restricted set of operations are included. This is the case for mechanisms putting an explicit price on carbon such as the European Union Emissions Trading System, the Australian carbon tax or the Californian Emissions Trading Scheme. In those cases, the MRV occurs at the scale of individual facilities.

The 'project scale' includes emissions stemming from specific emissions reduction projects. These projects are often focused on a given activity, such as destroying an industrial gas or spreading the use of efficient cookstoves. The number of entities and the geographical area considered are then adapted *ad hoc* to the considered activity. The main example is offset projects, be they certified by the dominant Clean Development Mechanism of the United Nations, or by other standards such as the Verified Carbon Standard or the Gold Standard. As opposed to the two other scales, at the project scale the MRV of GHG emissions is always combined with the MRV of GHG emissions reduction: both the project emissions and its counter-factual — or baseline — emissions are monitored, reported and verified at the same time, and along the same rules.

Dealing with uncertainty

The last important concept for this Review is the uncertainty associated with emissions MRV. This concept involves a flurry of terms that are not always understood in the same manner. We adopt the terminology of the IPCC[6]: uncertainty corresponds to the difference between the estimate and the actual value. Hence, it covers the two types of errors that are commonly distinguished: systematic errors or bias that decrease the accuracy of the estimate (for example a miscalibrated gas meter, or unit error in the reporting) and random errors that decrease the precision of the estimate (for example sampling error, errors of copy in the reporting). In monitoring, lack of accuracy and of precision can both lead to uncertain estimates, but only the second can be dealt with by increasing the number of samples. Bias can only be reduced by monitoring and reporting the same source of emissions with a change in the method. In reporting, both types of errors can be reduced through quality control and verification.

MRV trade-offs

Scale and uncertainty lead to the two necessary trade-offs in the MRV of GHG emissions, as explained by Cochran[3]: cost versus uncertainty, and information relevance versus comparability. The trade-off between cost and uncertainty is one of the key threads of this Review. For each CPM considered, we identify whether flexibility provisions are in place to adapt uncertainty requirements to the cost incurred by stakeholders. These provisions may take the form of *de minimis* thresholds (that is, threshold levels of emissions under which monitoring and reporting are not required), or 'materiality thresholds' (that is, threshold levels of errors under which errors are tolerated during verification). They can also take a more continuous form, for example by increasing the cost of compliance or discounting the benefits from carbon credits in proportion to the uncertainty of monitoring.

The second trade-off, between information relevance and comparability, comes from the difference in information needs from case to case. A country with only a few trees, such as Monaco, will see the quantification of emissions from its forestry sector as a complete waste of resources when it comes to designing climate mitigation policies. But Canada or Brazil may not see it that way. However, letting each country choose the sources it monitors, the method it uses to report them and the format under which all this is reported would greatly hamper the comparison of emission levels between countries. The same goes for cities, companies and offset projects depending on their specific context and needs.

In a nutshell, five cross-cutting questions are asked on the schemes being reviewed:

(1) What are the key MRV requirements?
(2) What are the costs for entities to meet these requirements?
(3) Is a flexible trade-off between requirements and costs allowed?
(4) Is requirements stringency adapted to the emissions amount at stake (materiality)?
(5) What is the balance between comparability and information relevance?

MRV requirements across schemes

The first cross-cutting question — what are the key MRV requirements? — is too large to be answered in a synthetic way. This section thus focuses on two components of this question that have a major impact on MRV costs: requirements pertaining to third-party verification and those pertaining to monitoring uncertainty.

Verification requirements are broadly similar across the board. Most CPMs impose a verification of the reports by an independent third party. Verification requirements are broadly similar across CPMs (Fig. 1): first, the third party must be accredited by the regulator for GHG emissions audits and this accreditation tends to be sector-specific; second, the third party must assess whether the methods used and the reporting format comply with the relevant guidelines; third, the third party must assess the accuracy, that is, the absence of bias, of the reported figures; fourth, the regulator

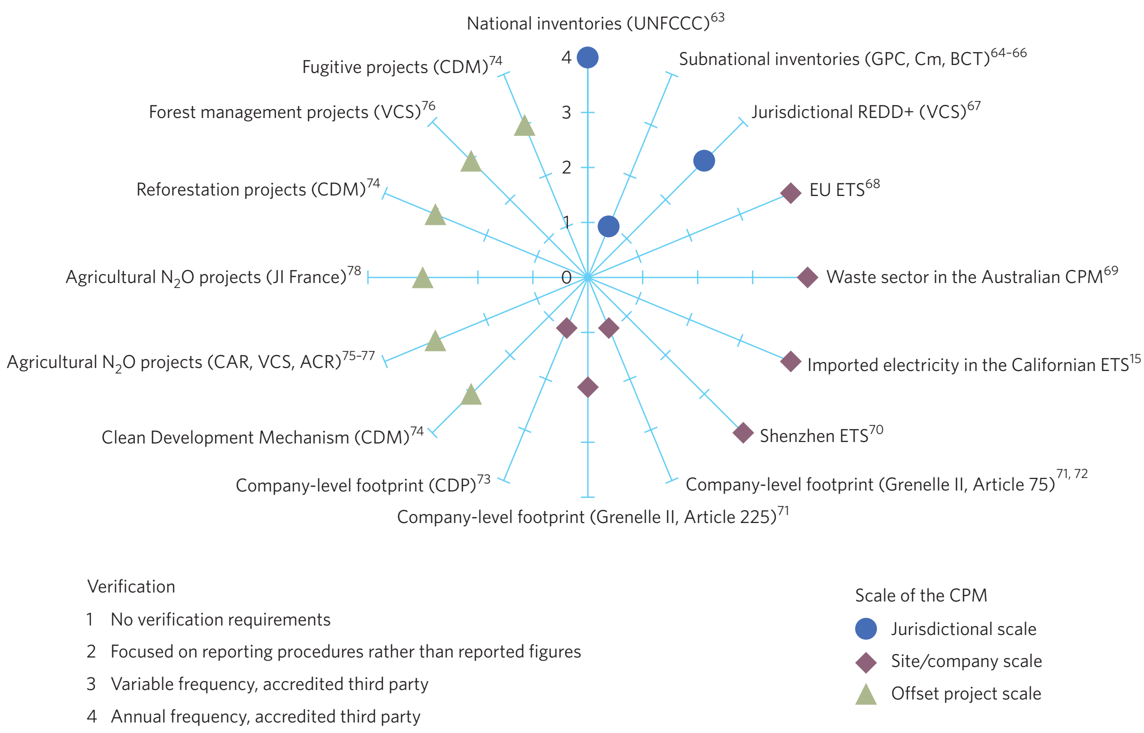

Figure 1 | Typology of verification requirements across CPMs. For a detailed justification of the typology, see Supplementary Table S1. Abbreviations are defined in Table 1.

is allowed to question the opinion of the auditor, but seldom does so; and fifth, the third party tends to be paid directly by the verified entity. Although this creates a potential conflict of interest, the risk of losing the accreditation is a much stronger incentive and keeps auditors from being complacent with their client[7]. Random verification of a few entities only — as is the case for small projects under the Gold Standard and for small installations under the Australian Carbon Pricing Mechanism — is uncommon: the auditor is then paid by the regulator. The verification of national GHG inventories under the UNFCCC is also not directly paid by the countries under review.

Some details may differ (Supplementary Table S1). Verification frequency is one example: it tends to be annual for most CPMs at entity scale, whereas it is variable — decided by the project proponent — at project scale. The emphasis put on individuals also varies across schemes: UNFCCC accredited reviewers act in their own name, and so do auditors in California and Australia. Under the EU Emissions Trading System (ETS) and the CDM, however, it is firms rather than individuals that are accredited, although one of the key criteria to obtain accreditation is of course to secure individual competence either internally or through long-term subcontracting. Note that Member States have some leeway on the accreditation procedures for EU ETS verification. As a result, and although most countries accredit firms, some accredit individuals.

The only schemes that stray away from these general observations are the schemes with little financial stake: subnational inventories and company-level footprints. The latter are nevertheless often verified: verification is incited under the Carbon Disclosure Project (verified respondents get a higher score within their transparency rating), and it is even mandatory for some companies under the French Grenelle II law (Article 225). Yet these verifications are peculiar: what matters is the reporting procedures of the company — do they ensure the internal consistency and 'fairness' of the reported figures? — rather than the accuracy and precision of the figures. In addition, the requirements on the expertise of the third party on GHG emissions is rather limited in these schemes: indeed, companies tend to use their financial auditors, which saves time as they are already familiar with the company structure and its accounts.

Requirements on monitoring uncertainty are seldom comprehensive. Sources of monitoring uncertainty are multiple. When calculation methods are used, there are as many sources of uncertainty as there are variables and parameters used in the calculation. Methods exist to combine the uncertainty from all sources in order to produce a comprehensive estimate (see for example GHG Protocol[8] or IPCC[6]). Yet CPMs seldom set a requirement on the overall uncertainty of a given source. The case of direct measurement in the EU ETS is a notable exception. The EU ETS and a few offset project methodologies get close to an overall requirement, as quantitative requirements are set on most sources of uncertainty — activity data and emission factors — involved in the calculation method. Most schemes also require a minimum calibration frequency when instruments are used. This frequency is often borrowed from existing national or international standards. The impact of calibration requirements on the actual uncertainty may be significant but is difficult to quantify across sectors and schemes[9].

The majority of CPMs, however, only set quantitative requirements on a few sources of uncertainty (Fig. 2, Supplementary Table S2). When financial stakes are low — that is, when mechanisms are primarily about accounting and tracking rather than directly pricing carbon, as in most jurisdictional schemes or for company-level footprint — the requirements are either qualitative, for example using a context-specific emission factor for major sources, or nonexistent. Hence, most CPMs exert only a partial control over the uncertainty that is reported.

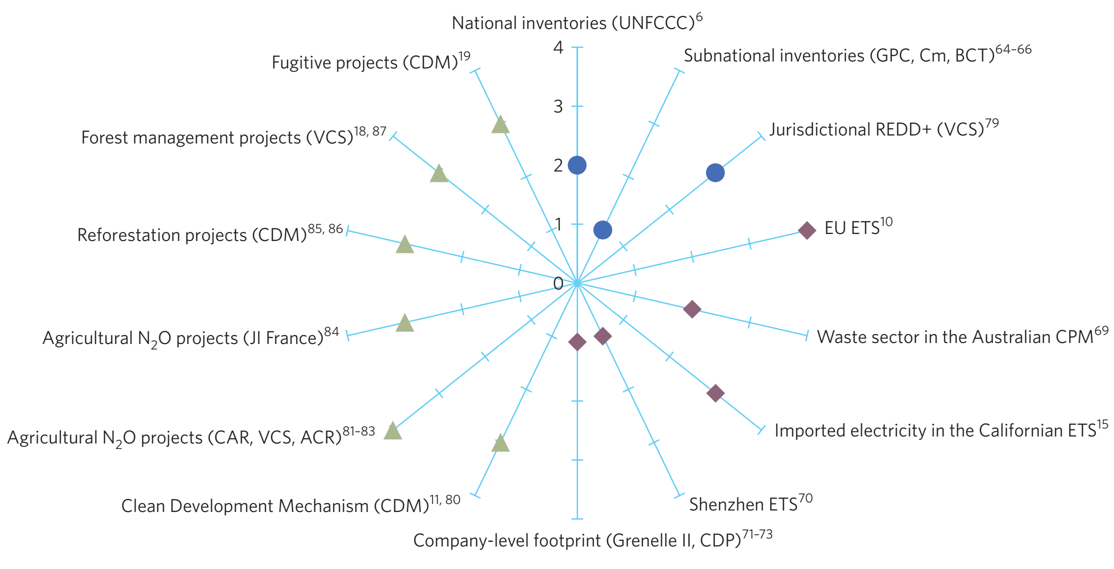

Figure 2 | Typology of uncertainty requirements across CPMs. For a detailed justification of the typology, see Supplementary Table S2. Abbreviations are defined in Table 1.

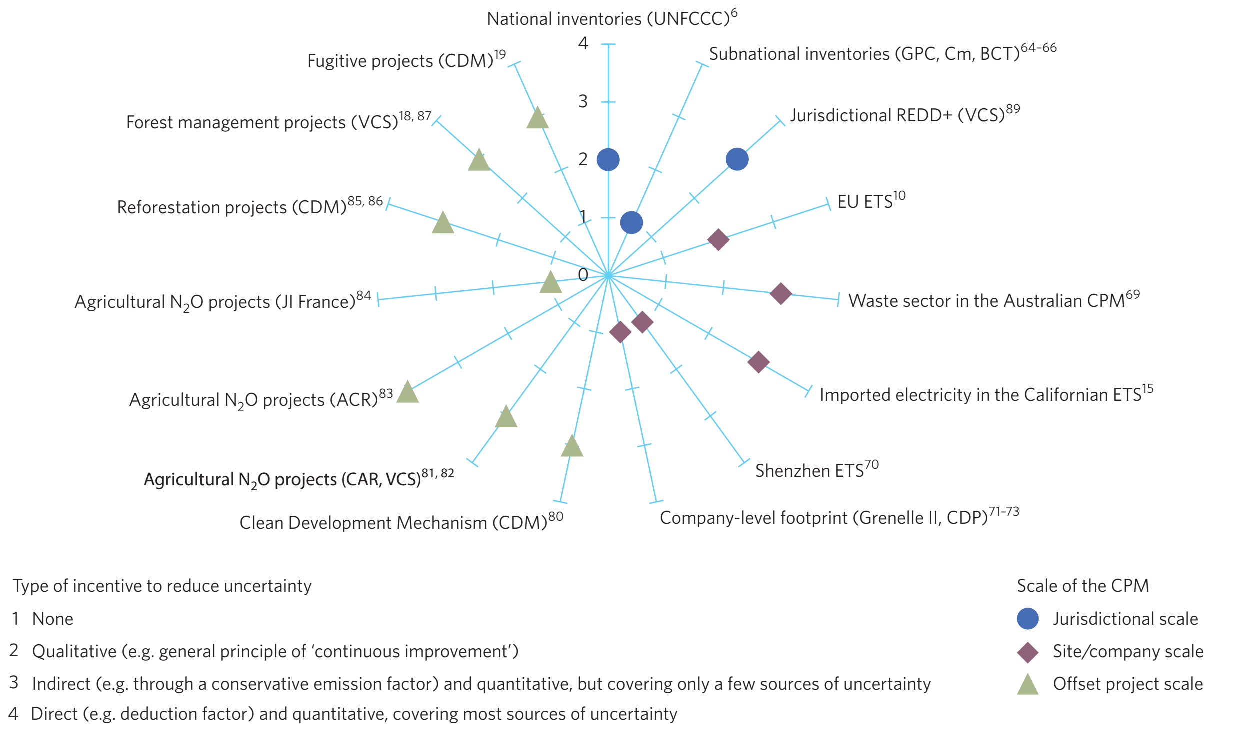

Figure 3 | Typology of incentives to reduce uncertainty across CPMs. For a detailed justification of the typology, see Supplementary Table S3. Abbreviations are defined in Table 1.

Incentives to reduce monitoring uncertainty

MRV concepts and principles are often presented without significant attention to how they are applied in practice. Incentives to reduce monitoring uncertainty, and in particular the 'conservativeness' principle, perfectly illustrate this gap between theory and practice.

Conservativeness: gap between principle and practice. 'Conservativeness' means that when the data are uncertain, a conservative value should be used so that emissions are not underestimated. This principle is commonly interpreted as an incentive to reduce monitoring uncertainty, often by adding one or two standard deviations to the estimate. If it were so, conservativeness would indeed provide an implicit incentive to reduce uncertainty.

But in practice, most of the rules in CPMs do not discourage the use of default values or the uncertainty of the monitoring method (Supplementary Table S2). For example, the IPCC guidelines for national GHG inventories allow for any type of uncertainty range, provided that the estimate is not biased[6]. The EU ETS limits the uncertainty of some elements but does not reward further uncertainty reduction as long as the threshold is met[10].

The CDM Executive Board has yet to clarify and systematize its application of the conservativeness principle, except in the case of surveys and samples[11]. Although some CDM tools and methodologies are already awarding fewer credits in proportion to reported uncertainty, this is not systematic. Many CDM methodologies provide an implicit incentive to reduce uncertainty by using conservative default values for some parameters or variables[9]. Yet these incentives remain limited in the CDM for three reasons[12]. (1) In most cases, conservativeness only concerns one or two parameters whereas there are often 10 or more parameters involved in the calculation[13]. These parameters were possibly chosen during the validation of the methodology as the most influential ones based on expert judgement. But this leaves out many sources of uncertainty whose importance has not been assessed in a systematic manner. (2) Conservativeness is only applied to the most uncertain option out of three or four possible monitoring methods (see for example the case of net calorific value of fuel in ref. 14). (3) An alternative method to the conservative default value is not systematically offered in the methodology. When this happens, a project proponent wishing to be rewarded for further reducing uncertainty will have to appeal to the Methodology Panel to revise the methodology. The resources — time and technical — necessary to undertake such a step represent a significant barrier.

Conservativeness is not a panacea. There may be good reasons not to be conservative when monitoring emissions. One is that conservativeness gives a competitive advantage to larger installations or entities where economies of scale make it economically feasible to use fewer default values and more precise monitoring methods (see 'Economies of scale', below). In the EU ETS, this would exacerbate the distortion created by MRV costs and probably explains why the regulator has abstained from embedding conservativeness in the Monitoring and Reporting Regulation (MRR). In California, the default emission factor applied to imported electricity is rather generous: it corresponds to a clean gas power plant[15]. This is the very contrary of being conservative, but it was probably necessary to avoid judicial proceedings from neighbouring states for breaching the constitutional right to free interstate commerce[16]. The European Union faced a similar dilemma when setting an emission factor on oil produced from Canadian tar sands under the Fuel Quality Directive[17]. In offset schemes, however, the risk of adverse selection offers a strong argument in favour of conservativeness.

Should there always be an incentive to reduce uncertainty? Although generally rare, incentives to reduce monitoring uncertainty are embedded in a small number of CPMs (Fig. 3, Supplementary

Table S3). Some offset project methodologies discount the number of credits issued in proportion to the overall monitoring uncertainty (for example VCS VM012 on improved forest management[18]) or in proportion to the uncertainty of one component of the estimate (for example leak flow rate in CDM AM0023 on fugitive emissions[19]).

These provisions may make sense in offset schemes that are vulnerable to adverse selection[20]: project proponents who benefit from the error — because their monitored emissions reductions are by chance above the true value — are more likely to join than those whose emissions reductions are underestimated. This selection bias eventually produces an overestimate in the aggregated total, despite the random nature of each individual error.

But economic theory and literature do not provide unconditional support for incentives to reduce uncertainty[21]. In general, uncertainties tend to balance out rapidly with an increasing number of emission sources and therefore tend to be of little concern. Exceptions may emerge in specific cases of information asymmetry or when a scheme encompasses only a few large sources.

Indeed, the regulator should in theory worry more about bias than about precision. And in many configurations, reducing the reported uncertainty does not reduce the risk of bias. To reduce the risk of bias, the expert judgement of independent and competent auditors is likely to remain the best-suited approach. A probably costly alternative would be to require a second estimate obtained from a different and independent method.

In practice, there is no clear consensus among regulators on the importance of monitoring uncertainty. The European Commission cites the large uncertainty of waste emissions as one of the main reasons to keep the sector outside the EU ETS[22], whereas this uncertainty did not visibly hinder Australia from including the waste sector in its CPM. Based on economic theory and the existing literature on this topic alone, it is not possible to determine clearly who made the best choice.

Economies of scale

Economies of scale are the dominant feature of MRV costs, at least when these costs are compared on a basis of cost per tCO_2e. These

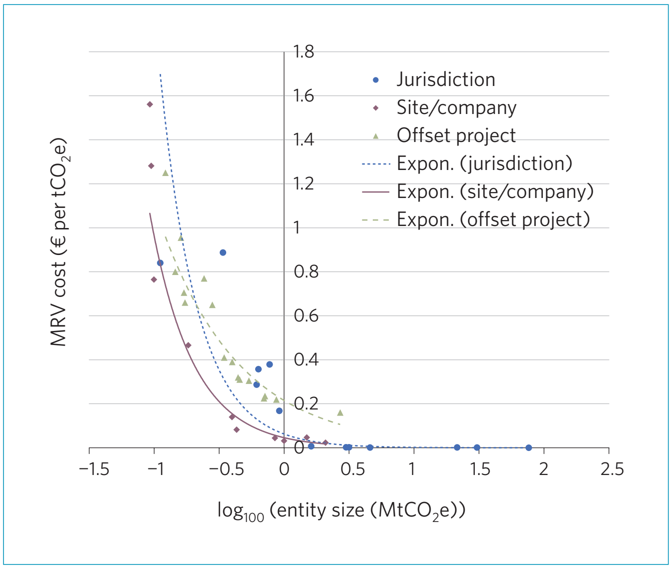

Figure 4 | Economies of scale in MRV. Each point corresponds to one of the (cost, size) pairs retained in ref. 1. It can be either an average for a given size range (for example EU ETS, CDM) or the estimated value for a specific entity (for example Germany's national GHG inventory, or a specific jurisdictional REDD project). As a result, all points do not have the same representativeness. The full list of pairs is provided in Supplementary Table S5. Expon., exponential fit to data.

economies have an automatic component: the division of a given cost by a larger denominator; and an intended one: regulation, mandatorily applied to a large number of sources and entities, must not impose too heavy a burden on the complying entities as these cannot opt out.

MRV costs decrease with the comprehensiveness of the perimeter. The larger and the more comprehensive a scheme, the lower the MRV costs. Jurisdictional schemes tend to cover all sources within a jurisdiction, and this adds up to a large amount of GHG emission. As a result, they exhibit much lower MRV costs than other schemes per tCO_2e (Table 1).

However, even when the emissions amount per entity is comparable, for example between cap-and-trade schemes and offset schemes (such as couples between 0.03 and 10 $MtCO_2e$), comprehensiveness pushes MRV costs down (Fig. 4, Table 1). Indeed, entity-scale schemes tend to be mandatory and therefore to cover all entities that meet the inclusion thresholds (for example more than 20 MW for combustion installations under the EU ETS). As such, they must be especially careful with the costs that they impose on regulated entities as these may distort the market (for example by putting higher costs on smaller entities) or even put unbearable burden on some firms[9]. Conversely, offset schemes in which participation is voluntary cannot bankrupt participating companies through MRV costs: if they are too high, companies simply do not participate. In addition, one of the interests of running an offset scheme is to reveal information on abatement opportunities, monitoring techniques and costs[23,24]. In this context, there is a rationale for leaning towards higher MRV costs in order to obtain better information. This is likely to be why offset schemes tend to exhibit higher MRV costs than cap-and-trade schemes (Table 1).

MRV costs decrease with size. Even within the same scheme, MRV costs vary widely. A major factor explaining this variation is the size of entities (Fig. 1). Indeed, fixed costs or costs that increase only slowly with entity size are numerous within MRV costs. Most monitoring and reporting costs are insensitive to size: a single monitoring report, methodology, project design document, national inventory report or similar is needed per entity, no matter the amount that it emits or reduces. In monitoring, the costs of a meter do not necessarily increase with the amount of material (electricity, gas, and so on) that it measures. Similarly, sampling costs increase only in proportion to the square root of the sampled population. The same goes for verification: a large part of the workload is proportional to the amount of documentation provided, which is largely independent of the amount of emissions at stake.

After entity size, entity and sector complexity also plays into MRV costs[25]. A large refinery with hundreds of pipes, connections and gas streams is more difficult to MRV than a simple power plant with a couple of boilers. Similarly, two-thirds of emissions from cement manufacture usually come from decarbonation. The monitoring of these 'process emissions' involves a complex mass-balance approach in addition to the more common and straightforward 'activity data × emission factor' approach used for energy consumption (the remaining third). Across schemes such as the EU ETS, the US EPA GHG Reporting Rule, or the Californian ETS, refineries and cement factories face higher MRV costs: although cement factories are large and benefit from the aforementioned economies of scale, their monitoring costs under the US EPA GHG Reporting Rule are twice the overall average on a per tCO_2e basis[26]. Other types of industries are also impacted by their complexity such as electricity importers.

The share of verification costs. Contrary to conventional wisdom, verification is usually not the main part of MRV costs. It varies mostly between 0 and 50% of total MRV costs, with an average 31%

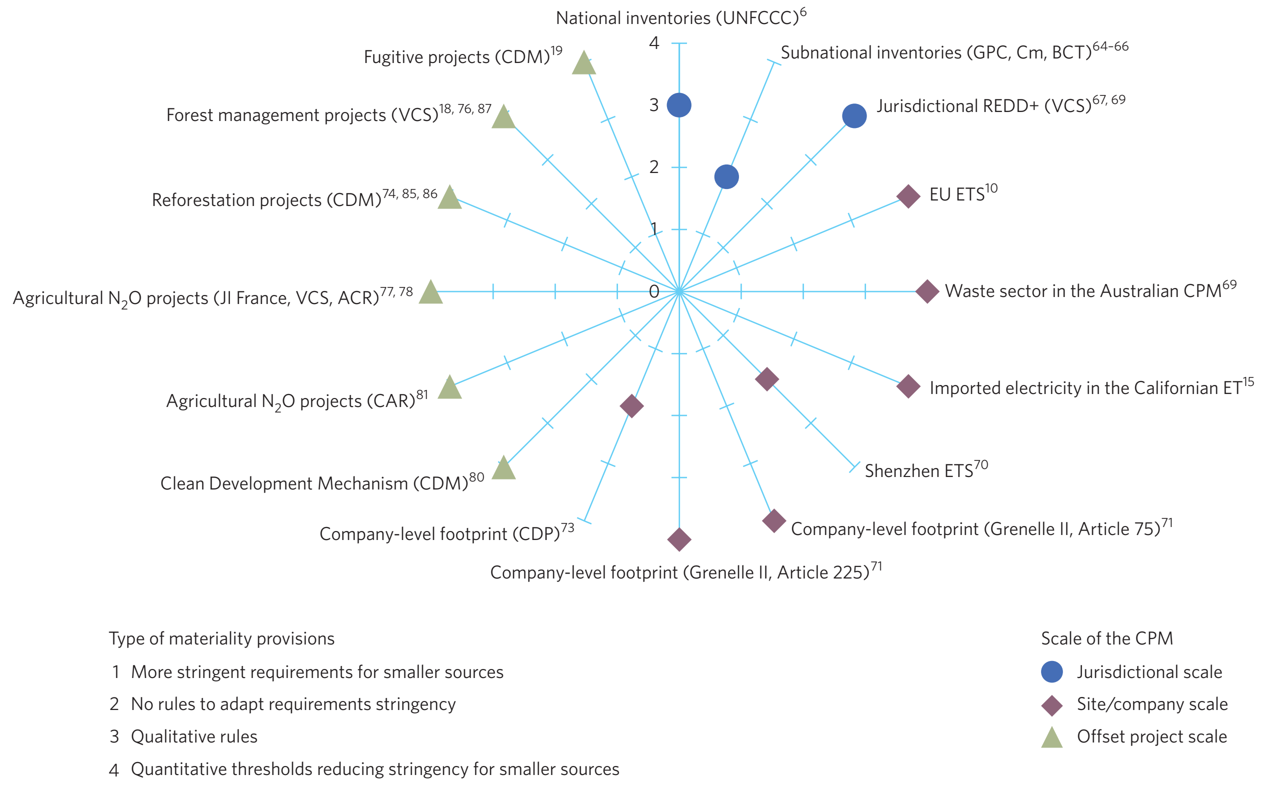

Figure 5 | Typology of materiality provisions across CPMs. For a detailed justification of the typology, see Supplementary Table S4. Abbreviations are defined in Table 1.

for the oldest and largest CPMs, namely national inventories, the EU ETS and the CDM (Table 1). Verification costs are, however, mostly fixed costs. For smaller sources or entities, it can therefore take the lion's share of MRV costs, up to 80% of the total[25]. Moreover, unlike monitoring and reporting costs, they cannot be internalized as the auditor must be an independent third party in most schemes.

Materiality does not outweigh economies of scale

Materiality is a concept that comes from the audit industry: an auditor should focus on the riskiest parts of what is being audited. In other words, one should pay more attention to larger numbers than to smaller ones. Materiality has made its way into the verification procedures of most existing CPMs: accredited auditors can only invalidate a monitoring report when errors exceed a given threshold (for example 5% of total facility emissions in the Californian ETS). Nevertheless, the concept of materiality is not taken into account in most jurisdictional schemes, either because verification does not take place (as is the case for most subnational inventories), or because the guidelines do not contain materiality provisions (which used to be the case for national GHG inventories) (Fig. 5, Supplementary Table S4).

The concept of materiality could be extended beyond verification to monitoring and reporting: fewer resources should be spent on smaller sources than on larger sources, or on smaller facilities than on larger facilities. Many provisions exist in carbon markets and carbon taxes to balance stringency with the amount of emissions at stake: smaller facilities are usually not covered by the scheme, and even within the scheme, the uncertainty requirements or the reporting frequencies are more lenient for these installations (Supplementary Table S4). Yet these provisions do not result in a level playing field. Economies of scale have the upper hand, and larger facilities and offset projects end up with lower MRV costs per tCO_2e (see below). Finally, national GHG inventories still largely ignore the concept: the requirements are almost as stringent for Slovenia as they are for Germany. This is not to say that the existing 'monitoring materiality' provisions are not useful: inclusion thresholds in particular are fundamental in limiting costs. The US EPA[26] assessed the effectiveness of a minimum threshold for inclusion in the perimeter of the regulation. Compared with the threshold of 25,000 $tCO_2e\ yr^{-1}$ retained in the United States, a threshold of 10,000 $tCO_2e\ yr^{-1}$ would increase costs by 35% and cover only 1% more emissions. Conversely, increasing the inclusion threshold to 100,000 $tCO_2e\ yr^{-1}$ would save 23% of the costs and cover 2.5% fewer emissions.

Comparability often trumps information relevance

Comparability between entities reporting within the same CPM is usually a top priority. As a result, most mechanisms offer little leeway in terms of scope, level of source disaggregation and even monitoring method.

All ETSs, taxes and offset projects define very precisely the gases and sources of emissions that are monitored. They also specify a common reporting format with a fixed separation of emissions sources. No leeway is left to the agent to adapt the scope or level of disaggregation to its own needs/constraints.

Monitoring methods are also closely restricted in ETSs, taxes and offset projects: although a choice is usually offered to the agent, it is limited to a few options for which instruments and emissions factors are explicitly listed.

Schemes and management systems with limited constraints or financial stakes such as subnational inventories and company-level footprint are the notable exceptions. Subnational inventories follow a variety of guidelines, and the guidelines themselves are limited to accounting principles and suggested emissions factors. Each entity is then free to choose, within the guidelines or elsewhere, the detailed equations, monitored variables and instruments that best suit its needs and constraints. These entities are usually undertaking their MRV as a means to assess the effectiveness of their internal mitigation strategy. They therefore extensively use the large leeway offered by the relevant MRV guidelines to adapt the MRV procedures to suit their specific needs. Cochran[3] illustrates this phenomenon with the GHG inventories of cities. For company-level footprint, the trade-off is a little more balanced: the possibility for outsiders to compare companies with one another and the repeated use of the same consultants within a sector to put together company-level footprints tend to foster comparability on scope 1 (site-level emissions) and scope 2 (electricity use). For scope 3 (upstream and downstream emissions), however, company-level footprints remain very heterogeneous.

National GHG inventories under the UNFCCC lie somewhat in the middle. Countries must use a very strict reporting format which makes comparison easy. But the choice on monitoring methods is almost unlimited as countries are always offered the possibility to use a 'Tier 3' method. Tier 3 tends to be whatever model the country proposes as long as some general criteria — for example that the model has been validated and published in the peer-reviewed literature — are met. Use of Tier 3 is fairly uncommon given that even lower tiers already offer significant leeway concerning acceptable activity data and emission factors. As a result, reported figures are not strictly comparable between countries, although verification, and in particular the use of comparison tools provided by the UNFCCC Secretariat, keeps heterogeneity within acceptable limits.

Conclusion

Regarding our five cross-cutting questions, one can conclude that conventional wisdom on MRV is not often promoted in existing CPMs. One would intuitively encourage quantitative requirements on emissions uncertainty, together with an incentive to improve precision. Most often, this is only partially applied, if at all. Further, the time and resources spent on small sources of emissions would be expected to be limited. Although this kind of 'materiality' is widespread, the softened rules for smaller sources are largely outweighed by economies of scale: in all schemes, MRV costs per tonne are primarily driven by the size of the source. This is not to say that existing MRV rules are ill-devised. First, conventional wisdom may be wrong. Economic models indeed struggle to justify the usefulness of incentives to reduce monitoring uncertainty when dealing with multiple small sources. Second, some phenomena, such as economies of scale, may be beyond the control of the regulator. MRV rules that create no market distortion are probably an unreachable goal.

These conclusions should be of great use to the scientific and industrial community currently designing new GHG monitoring technologies for use in existing CPMs:

(1) In most cases, technologies with lower uncertainty than current practices are unlikely to be adopted because the rules do not value reduced uncertainty. In particular, the so-called 'conservativeness' principle often invoked to demonstrate the economic value of improved monitoring techniques is specific to a subset of CPMs — offset projects — and is not applied systematically and consistently even there.

(2) A more promising outcome awaits technologies that would meet the uncertainty requirements of existing CPMs at a lower cost than is achieved by current practices. The figures provided in this Review on maximum uncertainty thresholds and MRV costs can be used as benchmarks by technology developers.

(3) An alternative could be to lobby regulators for regulations with more comprehensive and more direct incentives to reduce monitoring uncertainty. This would probably be perilous, as top-down regulations change slowly, in particular when there is no obvious rationale for the regulator to reduce monitoring uncertainty (see 'Incentives to reduce monitoring uncertainty', above). Bottom-up CPMs such as offset projects are easier to amend, but their market size plummeted during the second half of 2012 without any clear prospect of recovery[27].

Another cross-cutting conclusion to this study is that MRV rules significantly differ not only between 'scales' but also within them: the European Union, Australia, California and Shenzhen have set different MRV rules in their respective site-level CPMs. Five thousand sites with emissions lower than 25,000 tCO_2e per year undergo MRV under the EU ETS, whereas in Australia verification is only mandatory for sites emitting over 125,000 tCO_2e. The scope of the EU ETS is limited to heat and power generation and some industrial processes, whereas the transportation sector, imported electricity, and waste are included in some of the other schemes. Shenzhen even double-counts emissions from electricity.

Will these MRV differences lock the world into incompatible frameworks with different carbon prices? Not necessarily. When considering whether to link two CPMs, mutual confidence in their respective level of ambition is likely to be pivotal for the regulators involved. And this confidence can be obtained with reliable MRV procedures on both sides even if they are not strictly equivalent. Only time will tell.

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Author contributions
V.B. designed the study, analysed the pre-processed data and wrote the paper. V.B, M.A., E.A., A.B., J-P.C., C.C., I.C., M.D., C.D., C.F., G.J., R.M., R.R. and I.S. gathered and pre-processed the raw materials. N.S. coordinated data collection.

Additional information
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Competing financial interests
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Corrigendum: Monitoring, reporting and verifying emissions in the climate economy

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