

# Rock dust, crop nutrition and climate change

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## Abstract:

Soils are the interface between the geosphere and the biosphere. They provide the minerals required for crop nutrition, and they regulate atmospheric CO<sub>2</sub> to a greater extent than the ocean. These functions are often treated separately, with studies focusing on either crop nutrition or on soil organic carbon. The use of silicate rocks as remineralizers addresses both functions. Weathering releases nutrients, including silica, for crop growth, and consumes atmospheric CO<sub>2</sub>, generating bicarbonate in solution. If enough Ca is released, and with sufficient bicarbonate in solution, pedogenic calcite forms as a permanent sink for atmospheric CO<sub>2</sub>. This can be verified using C and O stable isotopes. The potential of silicate rocks for carbon capture can be estimated from their chemical composition, and varies between 70 – 500 kg CO<sub>2</sub> per tonne of rock. Life cycle analysis shows that the carbon cost of mining, transport and spreading to land allows transport for over 500-1000 km before the carbon cost exceeds the benefits. Land management can take advantage of these processes to both increase crop production and to increase soil carbon, both improving soil health and quality.

**Keywords:** soil; remineralizer; carbon capture; silicate; weathering.

## INTRODUCTION

The role of soils in mitigating anthropogenic CO<sub>2</sub> emissions has recently attracted considerable attention, given the targets that have been set internationally (e.g. COP21; Minasny et al., 2017) and nationally (e.g. the UK's legally binding target for net zero CO<sub>2</sub> emissions by 2050; UK Government, 2020). Initially focusing on soil organic matter, the '4 per mil' pledge sets out to increase soil organic carbon stocks by 0.4% (Minasny et al., 2017), but this represents an increase in a labile form of carbon, that can be removed through oxidation as a consequence (for example) of increased ploughing or other land management changes. An alternative approach focuses on inorganic carbon, either through the formation in soils of carbonate minerals such as calcite (Manning et al., 2013), or through enhanced rock weathering, in which atmospheric CO<sub>2</sub> is consumed during weathering and forms bicarbonate in solution, ultimately entering the ocean (Moosdorf et al., 2014). Combining soil fertility with carbon mitigation, Beerling et al. (2020) have shown that application of rock dust at scale to soil at 40 tonnes per hectare has the potential globally to remove 0.5 to 2 gigatonnes of CO<sub>2</sub> per year. In this context, it is important to consider the practical implications for the use of remineralizers in the context of CO<sub>2</sub> removal from the atmosphere. The objective of this paper is to estimate the CO<sub>2</sub> removal potential for Brazilian rocks considered as potential remineralizers, and to discuss aspects of their use for this purpose in the context of Brazil's agricultural emissions.

## MATERIALS AND METHODS

The potential to remove CO<sub>2</sub> from the atmosphere is calculated from the bulk chemical analysis of a rock, usually determined by XRF or using other methods with care to ensure a complete

analysis. As an example, this has been estimated for 11 Brazilian rocks or rock products, whose compositions are given in Table 1. These include kamafugite, basalt, granodiorite, dacite, phonolite, verdete and schist, some of which are already classified as remineralizers.

**Table 01** - Chemical composition of candidates for carbon capture.

wt%	Lourenço et al., 2017						Santos et al 2015		Araujo et al 2001		
	basalt	dacite	schist fines	phono -lite	grano- diorite	MBR8	retorted schist	verdete 4	verdete 13	mafurite L-6	ugandite L-28
SiO <sub>2</sub>	49.80	67.50	48.10	53.70	68.40	47.50	52.00	58.37	65.25	30.24	33.01
TiO <sub>2</sub>	-	-	-	-	-	-	-	0.61	0.60	7.06	6.18
Al <sub>2</sub> O <sub>3</sub>	12.70	12.40	12.90	21.40	13.90	9.30	11.50	12.02	14.02	3.59	5.97
Fe <sub>2</sub> O <sub>3</sub>	14.00	6.00	6.10	3.30	4.60	5.30	7.50	6.57	6.13	15.45	12.69
MnO	0.20	0.22	0.15	0.22	0.08	0.13	0.03	0.01	0.01	0.21	0.17
MgO	5.26	0.72	2.14	0.22	1.32	5.35	1.68	1.27	1.25	24.12	15.66
CaO	8.50	2.20	4.70	1.30	2.80	7.30	2.20	0.80	0.04	9.17	7.24
Na <sub>2</sub> O	2.50	2.40	1.30	7.10	2.50	1.30	1.20	0.21	0.15	0.86	3.35
K <sub>2</sub> O	1.43	4.63	1.76	8.37	4.08	1.76	2.53	6.33	9.04	2.17	3.52
P <sub>2</sub> O <sub>5</sub>	0.43	0.22	0.21	0.07	0.26	0.23	0.22	0.00	0.02	0.50	0.60
S	-	-	3.26	0.05	0.05	10.75	3.30	0.04	0.02	-	-
loi	-	-	-	-	-	-	-	-	-	7.63	12.43
total	94.82	96.29	80.62	95.73	97.99	88.92	82.16	86.23	96.53	93.37	88.39
<i>kg/t</i>											
carbCO <sub>2</sub>	66.7	17.3	36.9	10.2	22.0	57.3	17.3	6.3	0.3	72.0	56.8
eCaCO <sub>3</sub>	151.7	39.3	83.9	23.2	50.0	130.3	39.3	14.3	0.7	163.7	129.2
eMgCO <sub>3</sub>	110.0	15.1	44.8	4.6	27.6	111.9	35.1	26.6	26.1	504.5	327.6
erwCO <sub>2</sub>	218.8	93.6	114.6	152.5	107.4	197.6	81.9	76.8	85.7	522.7	396.4

*carbCO<sub>2</sub>* denotes CO<sub>2</sub> removed as CaCO<sub>3</sub> (Equation 1); *eCaCO<sub>3</sub>* and *eMgCO<sub>3</sub>* denote the amounts of equivalent CaCO<sub>3</sub> and MgCO<sub>3</sub>. *erwCO<sub>2</sub>* is the CO<sub>2</sub> removed by enhanced rock weathering (Equation 2).

The equations used to determine the carbon capture potential of a rock involve (1) the conservative assumption that all CaO within the rock combines with CO<sub>2</sub> to give a calcium carbonate product (Equation 1; Lefebvre et al., 2019), and (2) that enhanced rock weathering (ERW) involves Ca, Mg, Na and K, taking into account Ca bound as phosphate and sulfate minerals which are assumed to be unreactive to weathering via reaction with CO<sub>2</sub> (Equation 2; modified from Renforth, 2019).

$$\text{CaO} + \text{CO}_2 = \text{CaCO}_3: \text{CO}_2 \text{ (kg/tonne)} = 10 \times (44/56) \times \text{CaO (wt\%)} \quad (1)$$

$$\text{erwCO}_2 = \frac{44}{100} \cdot \left( \frac{\text{CaO}}{56} + \frac{\text{MgO}}{40} + \frac{\text{Na}_2\text{O}}{62} + \frac{\text{K}_2\text{O}}{94} - \frac{\text{SO}_3}{80} - \frac{\text{P}_2\text{O}_5}{142} \right) \cdot 10^3 \cdot 1.5 \quad (2)$$

In Equation 2, the factor 1.5 is the molar ratio of CO<sub>2</sub> to divalent cation, and is taken as 1.5 as a conservative global average (Renforth, 2019).

## RESULTS AND DISCUSSION

The results of the calculations are summarized in Figure 1. In this figure, it is assumed that selection of a material for increasing soil fertility is based on the potassium content; the same approach can be taken using other nutrients. Figure 1(A) shows that the CO<sub>2</sub> removal estimated for the precipitation of carbonate minerals decreases with increasing K<sub>2</sub>O content, and this is to be expected, as igneous rocks with high K<sub>2</sub>O are often naturally low in CaO. In contrast, when the alkali content, Na<sub>2</sub>O and K<sub>2</sub>O, and MgO are included with CaO, the amount of CO<sub>2</sub> removed

through enhanced rock weathering is much greater for all rock types, including those with high K<sub>2</sub>O contents (Figure 1B).

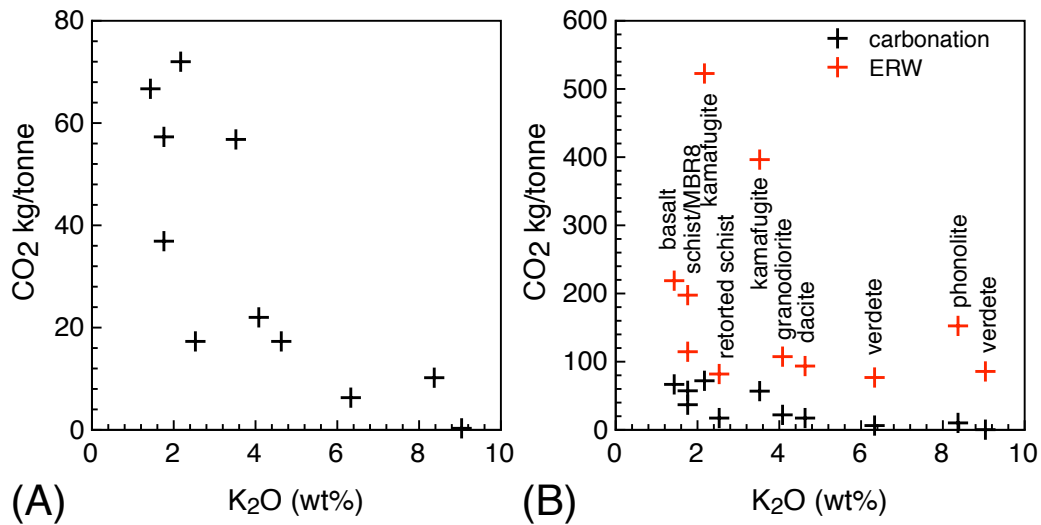


Figure 1. CO<sub>2</sub> removal for selected Brazilian rocks, estimated (A) assuming carbonate mineral formation (carbonation) and (B) assuming enhanced rock weathering (ERW).

The results summarized in Figure 1 clearly show that the basic and ultrabasic igneous rocks have the greatest potential for CO<sub>2</sub> removal, with the maximum values obtained for enhanced rock weathering of the kamafugites, whose chemical composition also appears to meet the requirements of IN 05/2016. The dacite, granodiorite, schist and one of the verdete samples fails IN 05/2016 as the sum of MgO + CaO + K<sub>2</sub>O is less than 9%, and these rocks also show low potential for CO<sub>2</sub> removal. Interestingly, despite its low MgO and CaO contents, the phonolite has sufficient Na<sub>2</sub>O and K<sub>2</sub>O to have a high CO<sub>2</sub> removal potential through enhanced rock weathering, although the potential to form carbonate is very low.

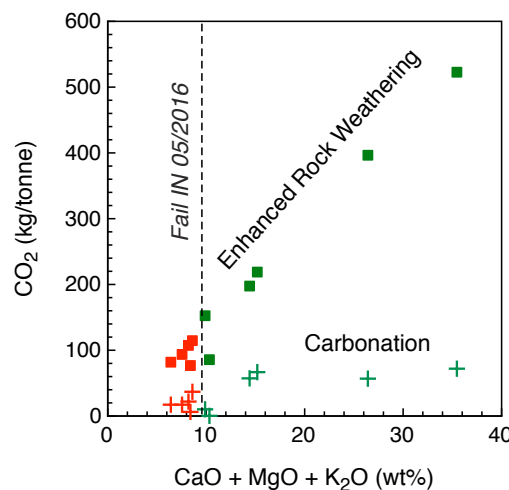


Figure 2. CO<sub>2</sub> removal compared with the sum CaO + MgO + K<sub>2</sub>O, which must be greater than 9% for compliance with IN 05/2016.

Figure 2 shows the CO<sub>2</sub> removal compared with the sum of MgO + CaO + K<sub>2</sub>O. Clearly, those rocks that fail IN 05/2016 as a consequence of this sum being below 9% have the lowest CO<sub>2</sub> removal potential. The kamafugites have the greatest CO<sub>2</sub> removal potential, then the basalts.

The product MBR8, from Lourenço et al. (2017), and the phonolite exceed this requirement within IN 05/2016, and have potential to remove over 100 kg CO<sub>2</sub>/tonne. On the basis of MgO + CaO + K<sub>2</sub>O, verdete 13 (Santos et al., 2015) meets the requirements of IN 05/2016, but could remove less than 100 kg CO<sub>2</sub>/tonne through enhanced weathering, and only 0.3 kg CO<sub>2</sub>/tonne through carbonation, given its very low CaO content.

Clearly, there is a carbon cost to the process of applying a rock dust to soil. This has been assessed rigorously using basalt/diabase mined in São Paulo state as a case study (Lefebvre et al. 2019). The distribution of quarries in the Lower Cretaceous Paraná volcanic province (Baggio et al., 2016) was mapped, and the carbon cost calculated for the processes of mining, crushing, transport and application to land. The composition of the basalt reported by Baggio et al. (2016) is similar to that cited in Table 1. The carbon cost of using this material exceeds the carbon benefit at distances of  $544 \pm 65$  assuming carbonation only, and  $994 \pm 116$  km assuming enhanced rock weathering. Given that the kamfugites considered here have more than twice the carbonation potential of basalt, they could be transported further before the carbon cost outweighs the associated CO<sub>2</sub> removal benefits.

Validation of the value of a remineralizer for crop growth can be demonstrated through carefully designed plant growth trials. However, validation of claims for CO<sub>2</sub> removal are more challenging. In principle, the amount of carbonate mineral that forms in a soil can be measured, as has been shown for artificial soils (e.g. Manning et al., 2013). Using C and O stable isotopes, it can be shown that carbonate minerals have a modern pedogenic origin, demonstrating that the process of carbonate mineral formation has taken place as a consequence of human interventions (e.g. Washbourne et al., 2015; Jorat et al., 2020). However, with enhanced rock weathering, although the amounts of rock added to a soil can be measured, it is not possible to take a soil sample after application and to unambiguously determine the amount of weathering for the treatment that has taken place. In both cases, the fact that the soil system is open means that the products of weathering, either precipitated carbonate minerals or solutes, are able to move through the soil profile. Moulton et al. (2000) showed how solutes derived from weathering entered groundwater and plant tissue, demonstrating that weathering had taken place, but also showing that the products of weathering disperse over a large 3-dimensional volume of geosphere and biosphere.

To achieve the very ambitious targets for CO<sub>2</sub> removal highlighted by Beerling et al. (2020), application rates of 40 tonnes per hectare are required. This is an enormous amount, and goes beyond what is normal practice for application of a remineralizer. For example, REMIN (Scotland) Ltd, a UK supplier of a remineralizer that matches the requirements of IN 05/2016, recommends 5 tonnes per hectare as a minimum application, and up to 20 tonnes per hectare as a ‘booster’ application (<https://www.reminscotland.com/home-3/how-to-use/>). Whilst an application twice the maximum recommended by a supplier might be good for business, it would result in the equivalent of a layer of rock dust about 2mm thick. How quickly this can be incorporated into the soil, preventing loss through erosion or wind transport, and the impact on soil biota of such a large amount, have yet to be demonstrated.

Brazil’s emissions from agriculture are approximately 500 MT CO<sub>2</sub>e/yr (Angelo and Rittl, 2020), and there are ambitious targets to restore 30 million hectares of degraded pasture (Batista et al. 2019). The contribution that remineralizers may make to mitigate CO<sub>2</sub> emissions are summarized in Figure 3. If applied to 1 million hectares (10% and 30% of land used for sugar cane and soy respectively) at 40 tonnes/hectare, remineralizers compensate 1-4% of Brazil’s agriculture emissions; the kamafugites achieve around 2% at 20 tonnes/hectare. Given the scale

of agricultural land management and restoration of degraded pasture in Brazil, it appears that significant mitigation of agricultural CO<sub>2</sub> emissions can be achieved using remineralizers.

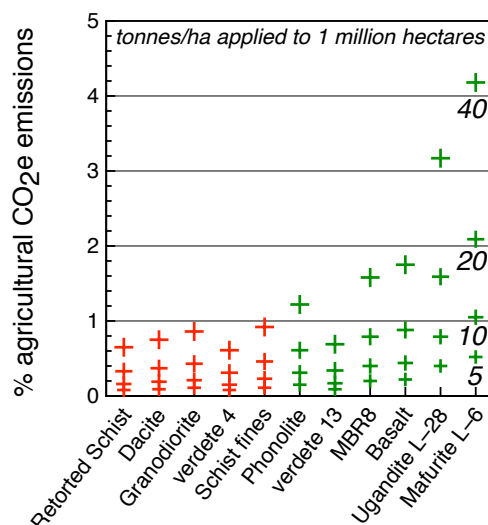


Figure 3. CO<sub>2</sub> mitigation potential, as % Brazilian agricultural emissions, of rock dusts (red) and remineralizers (green) applied at 5, 10, 20 and 40 t/ha to 1 million hectares.

## CONCLUSIONS

This study shows that remineralizers have potential for the simultaneous removal of atmospheric CO<sub>2</sub>, and so have potential to mitigate anthropogenic climate change. The basic and ultrabasic igneous rocks, including basalt and kamafugite, have the greatest potential and hold the possibility of forming soil carbonate minerals that can be used to verify CO<sub>2</sub> removal. Enhanced Rock Weathering gives much larger calculated values for CO<sub>2</sub> removal, but these cannot be verified easily from analysis of soil samples. Using 11 Brazilian rocks as examples, those igneous rocks that pass the IN05/2016 criteria that MgO + CaO + K<sub>2</sub>O should exceed 9% have the potential to remove amounts of CO<sub>2</sub> exceeding 100 kg CO<sub>2</sub>/tonne. Their widespread use in agricultural land management at a large scale has the potential to mitigate a significant proportion of Brazil's agricultural CO<sub>2</sub> emissions.

## REFERENCES

- ANGELO, C.; RITTL, C. SEEG 2019. Relatório-Síntese. Novembro de 2019. Observatório do Clima. [http://www.observatoriodoclima.eco.br/wpcontent/uploads/2019/11/OC\\_SEEG\\_Relatorio\\_2019pdf.pdf](http://www.observatoriodoclima.eco.br/wpcontent/uploads/2019/11/OC_SEEG_Relatorio_2019pdf.pdf)
- ARAUJO, A.; CARLSON, R.W.; GASPAR, J.C.; BIZZI, L.A. Petrology of kamafugites and kimberlites from the Alto Paranaíba Alkaline Province, Minas Gerais, Brazil. *Contributions to Mineralogy and Petrology*, v 142, p 163–177. 2001. <https://doi.org/10.1007/s004100100280>
- BAGGIO, S.B.; HARTMANN, L.A.; BELLO, R.M.S. Paralavas in the Cretaceous Paraná volcanic province, Brazil – A genetic interpretation of the volcanic rocks containing phenocrysts and glass. *Anais da Academia Brasileira de Ciências*, v 88, p 2167-2193. 2016. <http://dx.doi.org/10.1590/0001-3765201620150088>
- BATISTA, E.; SOARES-FILHO, B.; BARBOSA, F.; MERRY, F.; DAVIS, J.; van der HOFF, R.; RAJÃO, R.G. Large-scale pasture restoration may not be the best option to reduce greenhouse gas

- emissions in Brazil. *Environmental Research Letters*, v 14, 125009. 2019. <https://doi.org/10.1088/1748-9326/ab5139>
- BEERLING, D.J.; KANTZAS, E.P.; LOMAS, M.R.; WADE, P.; EUFRASIO, R.M.; RENFORTH, P.; SARKAR, B.; ANDREWS, M.G.; JAMES, R.H.; PEARCE, C.R.; MERCURE, J.-F.; POLLITT, H.; HOLDEN, P.B.; EDWARDS, N.R.; KHANNA, M.; KOH, L.; QUEGAN, S.; PIDGEON, N.F.; JANSSENS, I.A.; HANSEN, J.; BANWART, S.A. Potential for large-scale CO<sub>2</sub> removal via enhanced rock weathering with croplands. *Nature*, v 583, p 242-248. 2020. <https://doi.org/10.1038/s41586-020-2448-9>
- JORAT, M.E.; GODDARD, M.A.; MANNING, P.; LAU, H.K.; NGEOW, S.; SOHI, S.P.; MANNING, D.A.C. Passive CO<sub>2</sub> removal in urban soils: Evidence from brownfield sites. *Science of the Total Environment*, v 703, p 135573. 2020. <https://doi.org/10.1016/j.scitotenv.2019.135573>
- LEFEBVRE D.; GOGLIO, P.; WILLIAMS, A.; MANNING, D.A.C.; DE AZEVEDO, A.C.; BERGMANN, M.; MEERSMANS, J; SMITH, P. Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: a case study for Sao Paulo State, Brazil. *Journal of Cleaner Production*, 233, 468-481. 2019. <https://doi.org/10.1016/j.jclepro.2019.06.099>
- LOURENÇO, Y. dos S.; NACHTIGAL, G. de F.; SILVEIRA, C.A.P.; MARTINAZZO, R.; BAMBERG, A.L. Avaliação do crescimento micelial e esporulação de isolados de *Trichoderma spp.* em presença de diferentes fontes inorgânicas e orgânicas. In: BAMBERG, A.L.; SILVEIRA, C.A.P.; MARTINS, É. de S.; BERGMANN, M.; MARTINAZZO, R.; THEODORO, S.H. Anais III Congresso Brasileiro de Rochagem. Embrapa Clima Temperado; Brasília: Embrapa Cerrados; Assis: Triunfal Gráfica e Editora, 205-210. 2016. <https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1078602/avaliacao-do-crescimento-micelial-e-esporulacao-de-isolados-de-trichoderma-spp-em-presenca-de-diferentes-fontes-inorganicas-e-organicas>
- MANNING, D.A.C.; RENFORTH, P.; LOPEZ-CAPEL, E.; ROBERTSON, S.; GHAZIREH, N. Carbonate precipitation in artificial soils produced from basaltic quarry fines and composts: an opportunity for passive carbon sequestration. *International Journal of Greenhouse Gas Control*, v 17, p 309-317. 2013. <https://doi.org/10.1016/j.ijggc.2013.05.012>
- MINASNY, B.; MALONE, B.P.; McBRATNEY, A.B.; ANGERS, D.A.; ARROUAYS, D.; CHAMBERS, A.; CHAPLOT, V.; CHEN, Z.-S.; CHENG, K.; DAS, B.S.; FIELD, D.J.; GIMONA, A.; HEDLEY, C.B.; HONG, S.Y.; MANDAL, B.; MARCHANT, B.P.; MARTIN, M.; MCCONKEY, B.G.; MULDER, V.L.; O'ROURKE, S.; RICHER-DE-FORGES, A.C.; ODEHA, I.; PADARIAN, J.; PAUSTIAN, K.; PAN, G.; POGGIO, L.; SAVIN, I.; STOLBOVOY, V.; STOCKMANN, U.; SULAEMAN, Y.; TSUI, C.-C.; VÅGEN, T.-G.; VAN WESEMAEL, B.; WINOWIECKI, L. Soil carbon 4 per mille. *Geoderma*, v 292, p 59–86. 2017. <https://doi.org/10.1016/j.geoderma.2017.01.002>
- MOOSDORF, N., RENFORTH, P.; HARTMANN, J. Carbon dioxide efficiency of terrestrial enhanced weathering. *Environmental Science and Technology*, v 48, p 4809-4816. 2014. <https://doi.org/10.1021/es4052022>
- MOULTON, K.L.; WEST, J.; BERNER, R.A. Solute flux and mineral mass balance approaches to the quantification of plant effects on silicate weathering. *American Journal of Science*, v 300, p 539–570. 2000. <https://doi.org/10.2475/ajs.300.7.539>
- RENFORTH, P. The negative emission potential of alkaline materials. *Nature Communications*, v 10, p 1401. 2019. <https://doi.org/10.1038/s41467-019-09475-5>
- SANTOS, W.O.; MATTIELLO, E.M.; da COSTA, L.M.; ABRAHÃO, W.A.P. Characterization of verdete rock as a potential source of potassium. *Revista Ceres, Viçosa*, v 62, p 392-400. 2015. <http://dx.doi.org/10.1590/0034-737X201562040009>
- WASHBOURNE, C.-L.; LOPEZ-CAPEL, E.; RENFORTH, P.; ASCOUGH, P.L.; MANNING, D.A.C. Rapid removal of atmospheric CO<sub>2</sub> by urban soils. *Environmental Science and Technology*, v 49, p 5434–5440. 2015. DOI 10.1021/es505476d (open access). <https://doi.org/10.1021/es505476d>
- UK Government 2020 <https://commonslibrary.parliament.uk/insights/acting-on-climate-change-the-plan-for-net-zero-emissions-in-the-uk/>