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Carbon Leakage: Pollution, Trade or Politics?

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Abstract

Although in recent years carbon leakage has obtained broad attention in public opinion and environmental research, it remains a blurred concept. This is not surprising since there exist different, often vague definitions of this phenomenon that can be calculated using different (outcome-relevant) methods. The aim of the article is to bring clarity to this research field and give specific recommendations for good practice. In particular, different definitions and appropriate calculation methodologies will be critically discussed and compared. Crucial differences with respect to diverse research purposes will be highlighted, deficits and possible problems will be indicated. A review of literature from 1990*s*-on reveals how the concept of carbon leakage has evolved and how our perception of it has changed over decades. It shows also what we can learn from the past experiences.

Keywords: Carbon leakage, Environmental leakage, Environmental policy, Emission transfers, MRIO, EEBT.

1 What Is Carbon Leakage? 'Strong' vs. 'Weak' Approach

Carbon leakage (CL) is a teleological concept, thus it is contextual and goal-related. The most prominent and widely accepted definition of carbon leakage (CL) is set out by the IPCC and it reads as follows: *'the increase in CO_2 emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries'*(IPCC AR 4, WG 3, Ch. 11, 2007). This definition can be written as [42]:

$$CL = \frac{\Delta E_{area\ with\ no\backslash weak\ mitigation}}{-\Delta E_{area\ with\ strong\ mitigation}}$$

If the increase in the emissions of the countries with no or weak mitigation policy exceeds the emission reductions of the countries with relatively strong mitigation actions, the total emissions rise ($CL > 1$) which has an obvious negative effect on the environment. If that increase is positive, but smaller than or equal to the decrease in emissions in the mitigating area, then the environmental effectiveness of the emission reductions will be partially or totally offset ($0 < CL < 1$ or $CL = 1$ in the second case). It is however also possible that an emission decrease in the mitigating country will be followed by the emission decrease in the non-mitigating area and then the so-called negative carbon leakage occurs ($CL < 0$), e.g. as a result of an

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international technology spill-overs [15].[1]
It should be stressed that in general scientists consider only emission changes **due to environmental regulation** and disregard other emission changes resulting from different factors like labor cost advantage while calculating carbon leakage [20]. The same logic is applied also in studies dealing with leakage from forest conservation activities where only changes in wood extraction abroad evoked by the reduced deforestation in the regulated area are considered [32]. Such *policy-induced* type of leakage is commonly referred to as 'strong' carbon leakage and can be nicely illustrated in the following example. If a company decides to relocate its production line from EU to China because of more competitive wages and consequently increases its production emissions using Chinese technology, this will not be taken into account while calculating 'strong' carbon leakage [41]. It would be relevant only if the decision was motivated by the environmental policy in the EU. Such an interpretation is driven by the research goal of answering the political question, if carbon mitigation policies result in and thus are diluted by the increased carbon emissions in other, non- or less mitigating countries. In order to make the 'strong' CL formula more intuitive, the result is often multiplied by 100% which delivers a percentage rate of carbon leakage. It can be interpreted as the percentage by which achieved emission reductions in the countries with strong mitigation measures were offset by the emission increase in the countries with weak/no mitigation policy [46]. Thus, within the political framework 'strong' CL rate is often used to evaluate the performance of a particular climate policy.
The IPCC in the AR 4, however, does not state explicitly the above mentioned causality condition. On the contrary, it explains that *'an increase in local fossil fuel prices resulting,* ***for example****, from mitigation policies may lead to the reallocation of production to regions with less stringent mitigation rules (or with no rules at all), leading to higher emissions in those regions and therefore to carbon leakage.'*(IPCC, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Ch. 11.7.2, 2007). The casual remark that environmental policy could be one of the causes leading to carbon leakage (indicated by the word 'for example') automatically broadens the scope of the CL definition and leaves room for ambiguous interpretation. In the glossary of terms used in the IPCC AR 4, WG 3 the definition of carbon leakage is more descriptive. However, it still does not state explicitly the casuality condition (all emission changes due to environmental policy) that is the cornerstone of all 'strong' CL studies. It mentions baseline levels against which the emission changes should be measured, but it does not specify what kind of baseline is exactly meant. Had it be clearly stated, other ambiguities appearing in the glossary description of CL could have been avoided.
In most cases 'strong' carbon leakage is predicted as an ex-ante analysis by means of partial equilibrium or general equilibrium model [51]. In this type of studies authors estimate first the baseline scenario that would have occurred, if the carbon constraint was not introduced at all. In the second stage they estimate different future scenarios that are likely to occur under the considered policy [41]. The conducted simulations are based on a range of different assumptions and, thus, their results vary greatly. Furthermore, the differences in the scope of the leakage studies concerning territorial/sectoral coverage, investigated environmental policies etc. make it difficult to compare the results directly [51, 13]. There are also a few econometric studies trying to estimate CL using ex-post data. In this kind of studies emissions changes in the mitigation and non-mitigation area are calculated by comparing actual environmental policy data (future values are inferred from the past) with the counterfactual scenario without environmental regulation.
The difficulty to separate different effects influencing the change in the emissions as well as the great number of assumptions implied are the main drawbacks of the 'strong' CL approach. From

[1] When using the above mathematical notation of CL, the assumption of falling emissions under mitigation policy becomes crucial because negative values of carbon leakage could theoretically result also from the situation when the emission level rises both in the mitigating and non-mitigating country.

a different research angle, calculating change in the emission due to environmental regulations intentionally omits changes caused by other factors. However, *from the purely environmental point of view*, it does not matter, if the global emissions increase as a result of the carbon restriction in the industrialized countries, low wages in the developing world or increased trade flows evoked by customer preferences. Thus, under the 'strong' carbon leakage definition these increases in the global emissions go unnoticed. This is the result of the political nature of the 'strong' CL definition. Nevertheless, the omitted emission changes can be expected to be substantial. Continuous decrease in transportation costs, development of the communication as well as the promotion of free movement of goods and services have made international trade flows as easy and barrier-free as never before. Furthermore, relatively low labor cost, or tax exemptions to promote investment in the developing countries (with no or poor environmental rules) constitute another strong incentive to outsource the production or even relocate the whole enterprise to those areas [16].[2] Exactly this increased production in the developing countries matched by the relatively high consumption rates in the developed countries gave scientists the motivation to look at the carbon leakage from another perspective and arrive at the alternative 'weak' carbon leakage definition.

The main idea behind the 'weak' version of carbon leakage is to capture the emissions in the countries with no/weak mitigation policy emitted during the production of goods that satisfy the demand in the carbon-capped area [37]. 'Weak' carbon leakage disregards the cause of the emission change which gives a broader picture of CO_2 in the atmosphere and removes the troublesome causality requirement present in the 'strong' definition. One should be however cautious rephrasing it as demand-driven or consumption-induced leakage since this may be interpreted as another problematic casuality condition.[3]

Unfortunately, there is no single commonly agreed definition of the 'weak' carbon leakage. Peters et al. (2011) define 'weak' carbon leakage as '*the difference between the territorial and consumption-based emissions*', which is nothing else than the net emission transfer. It can be also computed by deducting emissions embedded in imports to the particular area from emissions emitted during the production of exports from that area. This results from the simple trade equilibrium relationship: Production - Consumption = Exports - Imports [37]. In the literature one can find also a gross version of the 'weak' carbon leakage definition, which accounts only for the emissions embedded in exports from non-mitigation to mitigation areas (see e.g. Peters and Hertwich (2008)). It is however not as well established as the concept of the net emission transfers.

One should note that 'weak' CL can be given in a static or in a dynamic sense. In the first case, it defines an amount of emissions that can always be calculated even in a static environment without any emission changes. In contrast, the dynamic mode measures the changes in the emission transfers. One can easily transform static 'weak' CL into its dynamic version through the mathematical construction of finite difference which is equivalent to subtracting the values obtained through static definition at two different points of time. In particular, the value of the dynamic definition will be 0 (respectively positive, respectively negative), if and only if the value of the static definition remains constant over time (respectively strictly increases, respectively strictly decreases over time).[4] This means that in a stable situation with no emission changes the dynamic definition would not indicate any leakage, while the static definition would return

[2] Goodspeed (2006) investigated the frequency of using tax exemption or tax reliefs in developing and OECD countries. His investigations showed that both types of tax incentives were more frequently used in developing than developed countries.

[3] In fact, in the forest conservation literature there exists a concept of demand-driven displacement that tries to capture the pure effect of increased demand for forest products [32]. It does so by comparing the actual difference between consumption and production with the counterfactual one that would have occurred if no forest conservation policy was introduced. Thus, it is distinct from the casuality-free concept of 'weak' CL.

[4] Please note that this is a discrete analog of differential. In that case, the derivative equals 0 (respectively is non-negative, respectively is non-positive) if and only if the function is constant (respectively weakly increasing, respectively weakly decreasing).

a meaningful value representing a particular amount of emission transfers for a given period of time (usually a year). However, many authors favor the dynamic definition because analyzing changes can help to recognize trends in emission transfers. Moreover, the dynamic mode fits most closely the change framework established by the 'strong' CL studies. An overview of carbon leakage definitions or leakage-related concepts used in the literature is provided in Table 2. Taking into account the hypothetical nature of 'strong' CL and uncertainties concerning final results, its 'weak' version seems to be more relevant in climate economic terms. However, 'weak' CL results should also be interpreted carefully with a lot of attention being paid to the definition used by authors and their respective research question. In particular, it can happen that larger 'weak' CL values can be accompanied by a global decrease in emissions in the case of a static net emission transfer definition. This can be illustrated by the example of two trading partners with substantial and continuously deepening differences in the environmental policies. Let us assume that an environmentally-concerned country or a region (e.g. EU) strengthens its carbon policies and as a result its production and exports will become less carbon-intensive. On the other hand, its trading partner (e.g. China) has a relatively weak carbon policy and does not achieve any carbon reductions in the production for the domestic market and exports. Comparison of the values of the net emission transfer at two different points of time A and B; that is before and after the decrease in the production emissions in the EU, reveals that net 'weak' CL increased which can naturally lead to an impression of worse environmental quality [22], (see Fig. 1). However, in the reality the total amount of the emissions embedded in trade decreased. This may first seem counterintuitive, but one should note that consuming imported goods with the same content of carbon as previously matched by a decrease in the domestic production emissions represents an increase in the imported emissions compared to own exports and thus a higher leakage rate than before. Analogously, under the assumption of constant emissions embedded in imports from China, loosening of the environmental standards in the EU could decrease the value of the net 'weak' CL but increase the total emissions volume.

This effect can have important implications for international climate politics. Environmentally concerned entities (like the EU) can easily become a higher net emission importer just by decreasing their emissions embedded in exports (imported emissions are held constant) [22]. This again can significantly weaken the incentives to innovate and develop new carbon-low technologies in the carbon-capped countries in order to avoid bad reputation on the international arena ('largest emission importer' etc.).

Altogether, 'weak' CL captures emission (increases) arising not only from the mitigation policies but also from the globalization process through international trade. This makes it an important tool in current climate economic research and policy. However, one should keep in mind that the result of the net emission transfer formula (used in a static or dynamic sense) is a single number, which is easy to comprehend. For political purposes its simplicity is definitely an advantage, but it can lead also to misinterpretations. Thus, it is advisable to always control the absolute values of the emission transfers from non-mitigating to mitigating country/area and vice-versa. Only this additional information allows to correctly assess any changes of 'weak' CL over time. One should also emphasize that increased emissions embedded in trade can result from many different factors such as e.g. trade imbalance [38], energy and carbon intensity of economy as well as trade specialization [22].

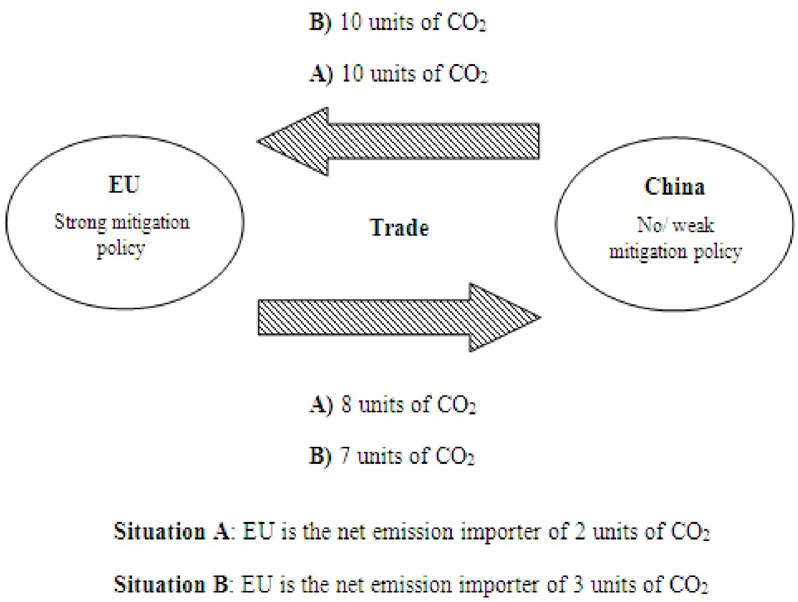

Fig. 1: Example of the net emission transfer (static definition) with a developed entity improving its carbon intensity of production

2 Calculation Method Makes a Difference

In order to calculate 'weak' carbon leakage one needs to know the difference between production and consumption accounts or equivalently the net emission transfer. The territorial emission data is recorded and widely available in many countries. However, estimation of the emissions embodied in imports/exports required for the net emission transfer and consumption accounts is much more challenging. Two most popular methods to account for emissions embodied in exports/imports are emissions embodied in bilateral trade (EEBT) and Multi-Region Input-Output (MRIO) method.[5] Both methods give different results with respect to the emission allocation between the countries, though the total global emissions are always equal [36]. This results from the fact that the MRIO method incorporates global network production interdependencies (e.g. semi-products produced in country C from raw materials from country A that will be finally consumed in country B), while the EEBT method investigates trade connections between two countries (e.g. country A and country B) including only the domestic production network (e.g. semi-products produced in A and used for the production of final goods in A to be finally consumed in country B). Peters et al. (2011) note fairly that the EEBT method is suitable, if one wants to investigate the share of emissions that originated **only** in the country A during the production of its exports [38]. However, nowadays due to global production networks emissions from the production of goods can be hardly attributed to only one country (they constitute usually some percentage of the total product emissions). Therefore, in order to capture the emissions embedded in exports/imports from the global supply chain at the place of final consumption one should use the MRIO method. Consequently, if one wants to estimate all emissions originating in non-mitigating countries that finally satisfy demand in the mitigation area (which lies at the core of 'weak' CL), the MRIO method will produce more precise estimates of the emissions embedded in exports/imports and thus lead to more accurate 'weak' CL.
The differences between the two methods are best reflected by the results of Peters et al. (2011). The authors estimated the emission transfers for the years 1997, 2001, and 2004 using EEBT and MRIO model. As expected, both models gave the same results with respect to the global

[5]Please note EEBT and MRIO are only tools to estimate emissions and they should not be confused with the notion of CL.

emission level and different estimates of the emission transfers and thus different estimates of 'weak' carbon leakage. The estimates are presented in Table 1.
Please note that both methods show a continuous growth in the emission transfers from Non-Annex-B to Annex-B countries. However, MRIO method returns values higher than EEBT. This is accompanied by increase in the emission transfers between Non-Annex-B countries. However, this time EEBT results in higher values than MRIO. Interestingly, the described differences between both methods in case of emission transfers from Non-Annex-B to Annex-B as well as between Non-Annex-B countries are almost of the same magnitude. These observations lead to the conclusion that due to supply chain globalization year in year out more semi-products are traded between Non-Annex-B countries before they are finally consumed in the Annex-B countries [38]. To better understand this relationship it is recommended to look at the computing manner of both methods. Due to inclusion of the global production network MRIO can assign emissions from extraction of raw materials/ production of semi-products in country A and emissions from processing it in country C to country B, that is the final consumption market. Under EEBT method extraction/semi-product production emissions would be assigned to the direct trade partner, country C and emissions occurring during the production of the final good in country C would be attributed to country B [38] (see Fig. 2).

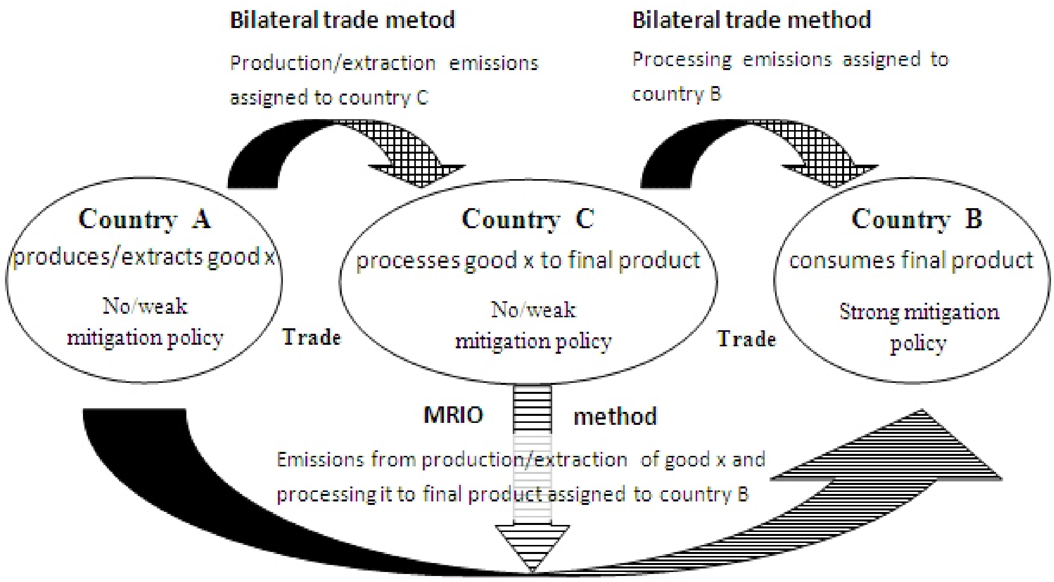

Fig. 2: Calculation scheme of MRIO and EEBT method

Also calculation of the emission transfers between Annex-B countries by means of EEBT and MRIO method shows different results: MRIO produces higher estimates than EEBT method. Discrepancies appear also during the estimation of the emission transfers from Annex-B to Non-Annex-B area; since 2001 transfers based on EEBT were bigger than those by MRIO [38]. Once again the differences between two methods in the case of emission transfers from Annex-B to Non-Annex-B turn out to be the same in magnitude. This can be interpreted as a signal that with advancing global supply chain diversification Non-Annex-B countries play more important role in the supply chain of the Annex-B countries. Based on the obtained results one could assume that Annex-B countries started to outsource some part of their production for the domestic market to Non-Annex-B countries. After processing the semi-products/ adding appropriate modules etc. goods are exported from Non-Annex-B countries to their destination market in the Annex-B area. Because the data used in the study covers only 3 years it would be desirable to investigate these changes over longer period of time in order to confirm these trends in the development of the emission transfers.[6] However, taking into account current outsourcing strategies of the companies from developed countries, such version seems to be very probable. The discussed divergences in the emission transfers between different regions lead naturally to the differences in the calculation of 'weak' carbon leakage. MRIO estimates of net emission transfers between Annex-B and Non-Annex-B countries exceeded estimates of EEBT by 48 Mt CO_2 in 1997, 171 Mt in 2001, and 278 Mt in 2004.[7]

Emissions embedded in trade (Gt CO_2)	EEBT			MRIO		
	1997	2001	2004	1997	2001	2004
Non-Annex-B to Annex B	1,366	1,694	2,251	1,415	1,822	2,449
Non-Annex B to Non-Annex B	0,748	1,045	1,443	0,700	0,916	1,244
Annex B to Annex B	1,957	1,856	1,863	1,956	1,898	1,942
Annex B to Non-Annex B	0,750	0,715	0,823	0,751	0,673	0,744
Net emission transfer [8]	-0,709	-0,978	-1,428	-0,664	-1,149	-1,705
Global Emissions	23,528	24,222	27,111	23,528	24,222	27,111

Table 1: MRIO and EEBT estimates of emissions embedded in trade and global emissions in 1997, 2001 and 2004. Source: Peters et al. (2011), Supporting Information Dataset 'Growth in emission transfers via international trade from 1990 to 2008'. Obtained with the permission of the corresponding author.

While only the MRIO method can produce estimates of the emissions embedded in exports/imports from the global supply chain, it comes at the cost of higher calculation effort and more demanding data requirements. In fact, data availability is the biggest problem connected with the MRIO method. The information concerning the final use and the geographical origin of the imported semi-products is in general difficult to trace and uncertainty rises with the degree of disaggregation [38], e.g. a Chinese company produces ships for the domestic consumption and for the US market. For the production it uses steel produced domestically and steel imported from Russia. In this case it may be not always possible to account for what kind of steel was used for a particular ship exported to USA. From the carbon accounting perspective this can make a big difference since steel is produced with a different carbon intensities in China and Russia. EEBT accounting only for the domestic supply chain constitutes a convenient simplification. This method can be particulary attractive to politicians interested primarily in the national emission accounts and solutions that can be relatively easy to implement in practice [39]. However, this calculation method should be applied and interpreted with caution because its simplicity can turn into oversimplification and result in ill guidance. In the extreme case, EEBT method could be even used by circumventing policies to influence environmental indicators in order to achieve desired results, e.g. lower 'weak' CL estimates. By introducing a redundant point of processing to the supply chain in one of the Non-Annex-B countries where only minor low-carbon adjustments are made (e.g. just before the point of the final consumption in the carbon-capped country), Annex-B countries could theoretically decrease the value of the 'weak' CL. In that case, the EEBT method would assign only emissions from the 'fake' minor low-carbon adjustments to the emission embedded in imports from Non-Annex-B to Annex-B countries. Abstracting from the risk of intentional politics, it is plausible to assume that the effectiveness of the environmental policies to decrease CL like Border Tax Adjustment could be increased, if carbon pricing was based on the true carbon content of goods covering emissions from the global supply chain. Thus, in order to decrease the risk of data abuse concerning 'weak'

[6] Peters et al. (2011) estimated missing years by developing the so-called TSTRD method that allowed them to construct data time series. However, due to multiple estimations this method is significantly more prone to errors than MRIO or EEBT.

[7] In order to create sense for these emission volumes, let us note that a 250 MW coal-fired power plant with at least 8000 operating hours per year emits annually about 1.7 Mt of CO_2 and 1.8 Mt of CO_2 a year is emitted by a typical steel producer for each 1 Mt of produced steel [9].

CL estimates and to increase the effectiveness of anti-leakage policies, it is recommendable to use the MRIO method to calculate carbon embedded in exports/imports despite its higher cost.

3 Concepts and Findings of Environmental Leakage in The Past

Already at the beginning of the 1970s environment was recognized as a restricted resource (just like material or labor) that should be allocated efficiently in order to obtain the optimal outcome [28]. From the late 1980s through 1990s a vast amount of literature was written on the topic of 'dirty' industry migration. At that time most economists considered re-location of the pollution-intensive industry as an economically efficient resource usage due to large differences in the pollution assimilative capacities, relative income and social preferences regarding environmental quality between the countries [28, 45, 12]. All these factors were perceived as country's comparative advantage and made it more or less suitable for being home to pollution-intensive manufacturing. This view was premise for the statement against harmonized environmental standards. In fact, many economists at that time argued for differentiated environmental product and process standards [48, 43]. On the contrary, concepts of '*pollution heaven*' and '*race to the bottom*' evoked concerns about the merits of the predominant approach towards the migration of 'dirty' industries. The main reason for that were the international disputes between developed and developing countries within the NAFTA agreement [49].[9]

A few decades ago the biggest producers of the 'dirty' goods were still developed OECD countries, although a growing interest in the 'dirty' industries like steel and iron could be already observed in many developing countries. Nevertheless, the conducted analyses did not permit to confirm that environmental regulation influenced the decision about the placement of the pollution-intensive industries. Low and Yeats (1992) showed that the share of 'dirty' goods in the total trade decreased by 3.5 percentage points between 1965 and 1988.[10] Neither environmental policy nor labor factor, but only raw materials were proven to have a relatively strong impact on the investors' decisions, especially in the pulp, petroleum, non-ferrous metals and cement industry. However, both authors admitted that a low level of country's development and slow technological progress may encourage the migration of 'dirty' sectors to 'pollution heavens' [28].

Lucas et al. (1992) could not prove the influence of the environmental standards on the migration of the pollution-intensive industry either. In their paper about the migration of the toxic industrial pollution they concluded that the share of the toxic manufacturing declines in the developed countries with the established environmental standards, however that trend is accompanied by the decline of the manufacturing in the total output [30]. This relationship, known as the composition effect, was the proof to one of three effects influencing environment through free trade described originally by Grossman and Krueger (1991). The authors investigated possible effects of the NAFTA agreement on the environment in Mexico and found out that trade liberalization within NAFTA should bring positive environmental results because of composition, scale and technique effects. The influence of the remaining effects on the environment was studied in many following papers. E.g. Lopez (1994) constructed two models in order to estimate the impact of the increased economic output on the environment due to free trade (i.e. scale effect). He argued that economic growth will not have any adverse environmental effects, if and only if economic output was dependent from the environmental quality [27].

The technique effect was handled e.g. by Wheeler and Martin (1992) in their paper on the pulp industry. According to their findings, open economies are more likely to adopt new and

[9] Empirical investigations have never confirmed environmental leakage understood as 'dirty' industry migration due to environmental regulation, either before or after NAFTA agreement entered into force [31].

[10] The data covered about 90% of the trade relationships at that time. People Republic of China and Africa were excluded from the analysis, however this fact is of minor importance since they did not play a significant role in the international trade during the investigated period.

environment-friendly technology [52]. Ishac Diwan in his comments on the article of Lucas et al. (1992) argued that developing countries with open economies have often cleaner technology than the social preferences of their citizens and their absorptive capacities would indicate. This is possible due to the international investors introducing new technology to the developing markets. A similar conclusion was reached by Birdsall and Wheeler (1993), who further argued that companies are not tempted by the differentiated environmental and industrial standards in the developing countries. They argued that companies are afraid of losing its image and credibility in the case of a serious accident. Furthermore, the cost and effort of adapting the old available technology to the production process are often higher than the implementation of the brand new technology. The authors noted also the growing importance of the 'green demand' resulting directly from the changes in the social preferences [6].

The greening of the consumerism was investigated in depth by Radetzki (1992), who motivated by the results of Grossman and Krueger (1991) continued to work on the relationship between pollution and income per capita. His research confirmed empirically that with rising income per capita pollution intensity declines (the phenomenon known as the Environmental Kuznets Curve) and income elasticity of demand for clean goods increases [44]. In addition, the richer the economy, the stronger is the compositional shift toward 'clean' industry. Economic development triggers also the establishment and further development of the property rights and policies. Therefore, the technique effect has also another positive impact on the environment. The investments in the new technology in the developing countries contribute to their welfare function. As a result, the citizens have more disposable income to spend on the environment-friendly goods that have a greater value to them.

Porter and Van der Linde (1995) investigated the link between pollution and technology as well, however they handled this topic from a company's perspective. By giving multiple examples they showed that companies forced to comply with stricter regulations often start to use materials in a more efficient way, subsidize inputs with less expensive substitutes and eliminate needless activities which decreases their total costs. However, the authors admitted also that non-competitive sectors like iron, steel, metal mining etc. (that are at the same time 'dirty') are likely to have a weaker innovation potential and therefore they may be more vulnerable to the strict environmental law. Jaffe et al. (1995) confirmed that the environmental regulation can pose a challenge to 'the dirtiest' industries, however, in general, it would constitute a rather small fraction of the average total production cost [21].

A breakthrough in the academic way of thinking about leakage came with the empirical study of Wyckoff and Roop (1994), who investigated carbon emissions embedded in trade on example of Canada, France, Germany, Japan, UK, and USA. The obtained results gave an empirical evidence that the weighted average of the carbon emissions embedded in imports to the mentioned countries during the mid-1980s accounted for 13% of their total emissions. Despite a few technical shortcomings (like e.g. equal carbon intensity of production, or lack of the feedback loop preventing double emission counting[11]) these findings can be viewed as an early warning to monitor the development of the carbon emissions embedded in trade and the prototype of 'weak' CL.

Summing up, the notion of leakage is not a new issue. In the previous decades its perception was strongly influenced by the principles of the welfare economics. This has been changing over time as governments started to pay more attention to the global character of increasing pollution and climatic changes. Current policy line is much more careful which is reflected in the modern environmental economics studies briefly summarized in the next section.

[11] In the model the carbon emissions can be counted twice when they are embedded in the exported sub-material and imported back as a final good.

4 Current State of Knowledge on Carbon Leakage

The research on carbon leakage boosted at the turn of the 20^{th} and 21^{st} century which can be explained by the increased political concern about environmental issues, especially the growing problem of global warming. New publications start to distinguish between different types of CL ('strong' and 'weak') and try to understand underlying mechanisms and key drivers. This issue will be discussed in the following sub-sections.

4.1 'Strong' CL studies

The identification of the channels through which 'strong' CL occurs was an important step in modern CL research. Their number depends on the degree of detail and focus of the corresponding study, however all of them relate to three main pillars:
1. Energy prices - carbon regulation consequently increases prices of the fossil fuels by aiming at internalization of the negative externality (CO_2 emissions). Higher fossil fuels prices result in a lower demand for this kind of fuel in the regulated area. This, in turn, lowers the world fossil fuel prices and thus encourages unregulated countries to use more often this type of energy.
2. Production (short and medium run) **and investment** (long run) - due to climate policies production cost of the carbon-intensive goods in the carbon-constrained area rises by a carbon premium. In many cases, the additional cost is shifted to the final consumers who start to seek for cheaper alternatives, e.g. imports of similar goods from the countries without any carbon regulation. As a result, domestic products may lose market share in favor of the carbon unconstrained importers which would be reflected in increased imports. In the long run, domestic investors facing carbon regulation may consider leveling the playing ground by re-locating production line to the areas without carbon mitigation measures. If the production in the carbon unconstrained area is 'dirtier' or at least as dirty as in the original region, the overall emission amount will rise (in the latter case the emissions from the transportation will tip the scale so that the final emission account will be positive).
This channel of carbon leakage is often vividly discussed on the political scene because it is strongly related to the national economy and labor market (outsourcing of production and loss of jobs). In the literature, scientists refer to it as 'competitiveness & investment channel' (Reinaud 2008) or 'industrial operation and investment effects' (Dröge et al. 2009). However, in the reality this channel is not considered to significantly increase the rate of carbon leakage, at least in the short and medium run.
3. Spill-overs - encompass all indirect (positive or negative) influences of the environmental policies and low-carbon technology on the emission level. E.g. Sijm et al. (2004) indicate that environmental policies may have substantial impact on the income in countries without environmental regulation and thus affect their emission level [46]. Carbon uncapped countries may also want to respond to the mitigation measures taken by other countries by adjusting their own emission level (up or down depending on the policy intention). Dröge et al. (2009) claim that strong environmental policy can influence the direction of the technological development and the type of the future investments in the carbon unregulated countries [13]. Unfortunately, these kind of 'side effects' are very difficult to measure, therefore they are often excluded from the CL analysis [18]. However, there are good reasons to expect that due to fast technological progress the influence of the technology spill-overs on the emission volumes will gradually increase, and thus they will gain more importance.
The estimated size of the 'strong' carbon leakage occurring through one (or a few) of the above mentioned channels will depend from the value of certain parameters and a couple of assumptions. E.g. the elasticity of the fossil fuel supply will determine CL arising from the energy channel. The more elastic the supply of fossil fuels, the lower will be the rate of carbon leakage. This can be explained by the fact that under elastic fossil fuel supply, fossil fuel producers adjust extraction to the current demand. Thus, lower demand due to carbon restrictions will

result in a lower extraction rate. Limited amount of the fossil fuels on the market will, in turn, prevent significant price decreases that could enable countries without environmental regulation to consume more fossil fuels. In the case of the inelastic fossil fuel supply, producers will extract the same amount of the fossil fuels regardless of the falling demand. The abundance of the fossil fuels will be consumed by the carbon-unconstrained countries at an adjusted, lower price. That effect can be additionally strengthened by the so-called Green Paradox described by Sinn (2008). According to Sinn's hypothesis environmental policy and announcements about its further tightening will encourage fossil fuel suppliers to extract more resources now than in the future. As a result, their supply will increase and even more fossil fuels will be available on the market despite falling demand in the carbon-capped countries. This could further push down the international price of the fossil fuels and deepen CL along the energy channel.

The relationship between CL and elasticity of the fossil fuel supply was studied in many papers [26], but the values of this parameter differ across the studies considerably.[12] This, however, matters as it obviously influences the estimated size of carbon leakage. Paltsev (2001) illustrated this nicely by using a sensitivity analysis in his study. In particular, he showed that CL rate estimated by the GTAP-EG model (which belongs to the computable general equilibrium family) decreases from 15% to 5% by increasing the elasticity of the fossil fuel supply from 0.5 to 20 [33]. In the face of widespread disagreements on the elasticity of the fossil fuel supplies (coal, gas, and oil) resulting from the gaps in the empirical research on that issue, it is highly recommendable to include sensitivity analysis in the simulation studies on 'strong' CL. Without a doubt, such a commonly accepted agreement on the 'strong' CL assessment methodology would create more transparency and help to better display energy market drivers underlying this phenomenon.

Another parameter widely recognized in the 'strong' CL literature is the ease of substitution between the products of different origin, known as the Armington elasticity.[13] It influences the size of the CL, particularly through the production channel as high values of the Armington elasticity make consumers switch to products produced in different regions more easily. However, just as in the previous case, the estimated values of this parameter vary depending on the study. Paltsev (2001) studied also the importance to the Armington elasticity of substitution in determining the overall size of the carbon leakage. He demonstrated that an increase of the rate of substitution between home and international products from 1 to 8 as well as between the basket of the imported goods from 4 to 16 units, rises the estimated leakage rate from 7% to 15% [33]. Burnieaux and Oliveira-Martins (2000) argued that the Armington elasticity can play a significant role when coal elasticity of supply is very low [7].

The estimation of the CL rate is further influenced by the model assumptions on abatement measures and their cost, ability of the producers to shift cost increases downwards the channel and the impact of the (future) environmental policies in other countries [51]. On the other hand, the degree of the international capital mobility strongly connected with the investment channel turned out to have very little influence on the CL rate at least in the short and medium run [33, 7].

Current economic models estimate the rate of 'strong' carbon leakage from the biggest agreement on GHG reduction - Kyoto Protocol - from a few percentage points to above 100% in a few extreme cases depending on the above mentioned parameters and other assumptions. E.g. Babiker (2005) estimated the size of CL resulting from the Kyoto Protocol in the long run to be 130% under the strong assumption of increasing returns to scale and homogenous goods in the energy-intensive sector [5]. However, the great majority of the ex-ante studies investigating the same policy assess 'strong' carbon leakage to fall into the interval between 2% and 20% [15, 7]. Available ex-post assessments of 'strong' CL are rather consistent about the limited impact of

[12]For an overview of CL rates and the applied elasticities in the CGE models see e.g. Sijm et al. (2008) or Gerlagh and Kuik (2003).

[13]The Armington elasticity formula consists of two layers: the first one measures the effect of substitution between home and international goods, the second one investigates the substitution among basket of imported goods only.

different environmental policies on the CO_2 emission level (see e.g. [1, 2] for the analysis of the Environmental Tax Reform in the European countries). One should however note that the number of such studies are significantly smaller than in the case of ex-ante modeling which can be partially explained by a rather modest number of relevant empirical data.

4.2 'Weak' CL studies

The prediction of predominantly moderate 'strong' CL development stands in sharp contrast to the diagnoses of 'weak' CL emerging from the empirical studies. The numerous papers on emissions embedded in trade published since 2000 indicate constantly growing emission transfers from non-mitigating to mitigating countries by trade [37, 4, 14].

The work of Wyckoff and Ahmad (2003) proving that OECD carbon consumption account was higher by about 5% than its carbon production account in 1995 (which constituted 2.5% of the global carbon emissions at that time) gave a solid premise to suspect that developed countries import significant volumes of the embedded emissions from carbon uncapped countries [3].

This issue was analyzed in detail by Peters and Hertwich (2008) by using more recent trade and emission data from 87 countries. According to their findings almost 22% of global carbon emissions of 2001 were emitted during the production of goods traded internationally. The net emission importers were developed countries that brought in about 44% of their total imported emissions from the developing countries [36]. This resulted in a carbon leakage rate from the Kyoto Protocol of 10, 8% according to the 'weak' CL definition used by the authors (see Table 2, Def. 5. CL in year 2001 expressed relative to the territorial emissions of Annex-B countries). However, based on the emission data published within that article 'weak' CL from the Kyoto Protocol, understood as static *net* emission transfer would be nearly a half of that, namely 5, 6% (see Table 2, Def. 3. CL in year 2001 expressed as percentage of Annex-B territorial emissions).[14] The authors calculated also leakage rates for individual countries (see Table 2, Def. 5. expressed as percentage of the territorial emissions in that country). The obtained estimated varied from 2.7% for Russia, 13.7% for Germany to 29.4% for Switzerland and Belgium respectively. Investigating these differences, the authors found out that large countries tend to have a smaller ratio of the emissions embedded in trade relative to their territorial emissions. This can be explained by the fact that these countries often produce many different goods on their own territory from the available domestic resources. Further, Kyoto signatories situated far from other Annex-B-countries were shown to have a higher share of carbon leakage of the total emission imports than those lying in close proximity to carbon-capped countries. Thus, the importance of the country size and distance acknowledged in the gravity model of trade was confirmed also in carbon leakage debate. The authors warned however of a superficial interpretation of the emissions embedded in trade. They noted that it would help to protect global climate if certain countries with particulary clean technologies and production processes became big emission exporters [36].

Peters et al. (2011) continued to investigate carbon embedded in global trade flows. By estimating CO_2 emissions embedded in trade from 1990 to 2008 they performed an analysis for 113 countries and 57 sectors. 'Weak' CL calculated as the net emission transfer from Non-Annex-B to Annex-B area was 2.82% in 1990 relative to the Annex-B territorial emissions at that point of time (see Table 2, Def. 3) which corresponded to 1.83% of world emissions. However, in 2008 the same CL indicator was already 11.51% (about 5.28% of world emissions) indicating a fast growth in the net carbon emissions imported by the developed countries (an average growth rate per year about 8%). Exports from developing countries, in particular due to non-energy intensive manufacturing, substantially contributed to that trend. Only emissions embedded in exports from China made up 75% of the total increase in the consumption emissions of the Annex-B countries. At the global scale, emission embedded in Chinese exports constituted 18%

[14]Please note that emissions embedded in trade were calculated using EEBT method. If they were calculated by using MRIO model, the outcome and thus 'weak' estimate would be most probably higher [37].

of the increase in the world CO_2 emissions [37].
Davis et al. (2011) investigated also the impact of international trade on global emissions. In particular, they observed that additionally to 'weak' CL, the emissions from (combustion of) fossil fuels traded internationally have severe implications for national emission accounts. However, it should be noted that this often goes unnoticed since the emissions from traded fossil fuels are attributed to the point of combustion and thus are often accounted as domestic production emissions. The calculations based on the international trade and industrial CO_2 emissions data showed that in 2004 about 23% of global emissions were embedded in trade and 37% of global emissions were generated from fossil fuels traded between countries. As a result, in many developed European and Asian countries $55 - 99\%$ of production emissions could be traced back to the imported fossil fuels. Even larger share of consumption emissions in these countries could be attributed to the net imports of fossil fuels and goods and services: 74.7% in Germany, 92.1% in Italy and over 98% in France, Japan and Switzerland [11].[15]
The analysis of Jakob and Marschinski (2012) further contributes to the unfolding research on the drivers of 'weak' CL. The authors decomposed emissions embedded in trade for USA, Germany, France, Japan, Russia and China and assigned them to the following factors:(1) trade balance, (2) energy intensity and (3) carbon intensity of energy in a given country as well as (4) specialization [22]. The results of that analysis revealed e.g. that almost 50% of US net carbon imports can be traced back to its trade deficit. Carbon intensity of energy was shown to significantly decease French carbon balance of trade. Unsurprisingly, the energy intensity of economies was proven to greatly increase the net emission exports of the developing countries. The obtained results made Jakob and Marschinski question the popular statement that 'weak' CL observable thorough international trade flows must be viewed as having a negative environmental impact. In particular, they argued that breaking trade relationships or introducing border tax adjustment (BTA) to decrease 'weak' CL could theoretically result in an emission increase. However, this effect strongly depends on the trade structure. Assuming two countries/regions produce two goods, the carbon leakage effect will occur if and only if the net emission exporter is specialized in the production of relatively clean goods (as compared to its total *domestic* production). Due to broken trade relationships or change in the relative goods' prices resulting from BTA, more of the so-far imported carbon-intensive goods will be produced for domestic consumption, in the country without environmental restrictions which increases global emissions. One should also note that the opposite effect should occur, if the net emission exporter is specialized in the production of relatively carbon-intensive goods. However, identifying country's trade specialization is non-trivial since the result largely depends on the input data. E.g. Jakob and Marschinski (2013) and Jakob et al. (2013) arrived at totally different results concerning China's trade specialization by using either GDP at purchasing power parity (PPP) or GDP measured by market exchange rates (MER). Consequently, they gave two different policy recommendations in respect to the implementation of BTA on trade with China.[16]
Pan et al. (2008) trying to explain the cause of the changes in the Chinese net emission transfers referred to the seminal analysis of environmental impact of free trade introduced first by Grossman and Krueger (1991). In particular, the authors argued that technique effect will lower or increase the net emission transfers of a country/region depending on the effectiveness of carbon intensity reductions relative to its trading partners. Consequently, countries that fall behind (re-

[15] The significant amount of the emissions from traded fossil fuels inspired the authors to propose an alternative way of internalizing CO_2 emissions and decreasing carbon leakage - carbon tax collected at the point of extraction. They argued that due to a relatively small number of countries extracting fossil fuels compared to those consuming them, such taxation could be a cost-efficient way to handle carbon leakage. A similar idea to introduce a mandatory payment covering costs of resource (petroleum) and its sinks (CO_2) in the OPEC countries was proposed by Daly [10].

[16] Similar problems are likely to appear in case of other developing countries whose GDP at MER is significantly lower than their GDP measured at PPP. This follows from the fact that the welfare of these nations under MER is usually highly underestimated because non-traded goods and services are mostly very cheap in these countries [8].

spectively take a lead) in carbon abatement will experience emission trade surplus (respectively deficit) assuming all other variables being constant. China managed to achieve efficiency gains in the past that prevented further increases of its net emission transfer. However, since 2002 Chinese economy energy intensity has increased. So did its carbon intensity of energy which can be explained by a heavy use of coal resources in the energy production.

The composition effect was also proven to affect net emission transfers. Assuming that the emission intensity of domestic consumption does not change, expansion of dirty sector in the domestic industry (and shrinking of a clean sector or vice versa) will lead to an increase (or a decrease if clean sector expands) in net emission exports. This effect is particulary significant due to specialization encouraged by free trade. Pan et al. (2008) reported a structural change in Chinese imports between 2001 and 2006 from textile to less energy intensive electronics manufacturing. Unfortunately, the mentioned emissions savings were overwhelmed by a 2% increase in exports of the most carbon intensive sectors [34].

Last but not least, the net emission transfer can increase, if country's trade surplus becomes bigger, ceteris paribus. This was the case for China that over six years increased its trade surplus by 240 billion USD. The authors concluded their assessment by saying that in general the cumulative impact of technique, composition and scale effect on net emission transfers cannot be predicted in advance. However, it will be surely influenced by comparative advantage (including environmental component or its lack) and national regulations (like regulation of exchange rates or granting export rebates as it was the case in China) [34].

Although the concept 'weak' CL is relatively new in comparison to the 'strong' CL, it has been constantly gaining in importance. However, it is not surprising since the empirical studies on the net emission transfers clearly indicate rapid carbon emissions increases resulting not only from environmental policies. In the light of globalization, thriving international trade, falling transportation and communication costs this constitutes a valuable piece of information that can be used to counteract further global emission increases. However, in order to adjust existing and/or introduce new measures that would effectively decrease GHGs, we need to continue the research on drivers of 'weak' CL.

5 Conclusion

The leakage concept originated in the late 1980s/early 1990s. However, its perception has changed considerably since that time which is reflected in the environmental economics literature. Due to strong confidence in the welfare economics environmental leakage used to be considered as a natural consequence of the optimal resource allocation. Nowadays, the thinking framework is totally different. Pollution has become a global problem and gained much in importance on the international political arena. It can be explained by the significant changes in the direction of the trade flows, their composition, and volumes that happened within a few decades. Technological progress allowed for a modular product design. Thus, the production of different parts could take place in the countries with the lowest production factor costs. The transportation costs were further reduced. Also an appropriate trade supporting policy facilitated the increase in the volume of the trade flows. World Trade Organization (WTO), established in 1995, contributed to the removal of barriers and/or reduction of the existing restrictions to the international trade. Increased political attention to problem of rising emissions had a positive effect on the carbon leakage research, that developed significantly over the recent years.

Nowadays, we distinguish between 'strong' and 'weak' type of carbon leakage. New studies consider various channels of carbon leakage, including not only industry re-location, but also changes in the fossil fuel prices as well as carbon embedded in the international trade. However, despite that undeniable progress, carbon leakage research is still an evolving science that needs clear rules and transparent methodology to systemize our knowledge on the topic and to proceed further. First, there is an urgent need for the clear-cut formulation of the definitions, possibly

using complementary unambiguous mathematical notations, that stress the exact scope and ultimate purpose of calculating CL. Are we interested in calculating changes in the emissions in the non-mitigating countries **due to** environmental policies in other countries in order to assess the effectiveness of these environmental policies ('strong CL')? If yes, what kind of environmental policies do we consider? Does support for renewable energy count as a mitigation policy too? Or do we want to account for all changes in the emissions embedded in trade between mitigating and non-mitigating area? Further, are we interested in finding out what volume of emissions embedded in trade with non-mitigating countries satisfies the increasing demand in the carbon-capped countries (static 'weak' CL) or do we want to measure the progress of that process (dynamic 'weak' CL)? This does not exclude field-specific approaches in the carbon leakage research with well-defined definitions like those coming from the forest conservation studies, e.g. measuring pure consumption-driven leakage. All of these research questions are possible and meaningful. However, the research community together with IPCC should officially acknowledge and stress the necessity of clear research statements, definitions and their notation using mathematical language to reduce uncertainty. We would like to start this process with this article, speaking out a plea for more transparency in the carbon leakage research. It would set clear boundaries for the scientists, reduce individual interpretations and thus make the carbon research more consistent. It would also contribute to a better understanding of the carbon leakage problem by the politicians in charge of environmental legislation. Without appropriate clarification of the notion of CL, e.g. in the next IPCC Assessment Report, it will remain a 'trendy buzzword'.
Further, a systematic approach towards 'strong' and 'weak' CL calculation methodology is needed to obtain reliable CL estimates. Firstly, all modeling studies should clearly state model assumptions and list applied parameters in order to minimize the black-box character. A sensitivity analysis showing how the model reacts to the changes in the parameter values could help to cope with uncertainty of the estimated parameters. Secondly, the consequences of using a particular method to estimate carbon embodied in trade should be clearly stated since its choice can significantly influence the final outcome. As we have shown previously, the divergence between the two methods will grow in size and importance with the progressing globalization process. The differences between calculation methods should be made particulary clear to the politicians because some methods are more prone to being misread or intentionally influenced than others, especially when the compliance with the environmental commitments is at stake. Last but not least, the researchers should not discard the legacy of past environmental leakage studies but rather try to learn from the past; search for analogies and interpret the situation development. In many cases available knowledge about environmental leakages could be directly applied in the field of carbon leakage and thus, we do not need to re-invent old ideas (e.g. reasons for which companies did not relocate abroad due to stricter environmental regulations, even over long run). This seems to be particulary important at the moment, when a large international scientific community is trying to crack the 'weak' CL problem looking for the explanation of its drivers and possible ways to counteract its negative environmental effect. There are some trials to adapt proven methods from the 1990s (e.g. decomposition of free trade effect on environment), however we strongly believe that the past knowledge could be used more extensively. E.g. older studies offer a broad range of empirical results, analysis and reflections concerning technology spill overs, induced technological change, etc. - topics that are still evolving, but crucial to future CL research.
Summing up, the establishment of clear and exact CL definitions, notation and transparent methodology, but also a glimpse into the past should further boost the development of the field. It would make it much easier to compare studies, draw appropriate conclusions and develop new high-quality research questions. It could also bring tangible benefits for the process of environmental policymaking reflected in well-thought, more effective and robust measures to counteract CL.

Type of leakage	Definition	Math. notation	Mode	Remarks	Reference
[1](Strong) carbon leakage	'(...) carbon leakage can be defined as the increase in CO_2 emissions in non-OECD regions that is the result of emissions restraints in OECD regions (compared to the Reference Case without restraints), stated as a percentage of the reduction in emissions in the OECD'.	$\frac{E_f - E'_f}{E_h - E'_h}$	Dynamic	This definition represents a typical interpretation of the carbon leakage concept in the CGE modeling. It may refer to any jurisdiction with environmental policy, be it a single country, economic union or international climate regime. Very important in this definition is the casuality condition that requires to consider only changes evoked by the environmental policy in the policy-restricted area.	E.g. Jacoby H. D. et al., 1996 or any other CL modeling study
[2] Policy-induced leakage	'(...) occurs when an increase in displacement ($C_h - P_h$) of wood extraction is due to a policy-induced reduction in domestic roundwood supply, with unchanged consumption of SPWP (secondary processed wood products) and exports.'	$PD = we_f - we'_f$ which is equal to: $(wIm - wEx) - (wIm' - wEx')$ under assumptions of: $wC_f = wC'_f$, $wEx = wEx'$	Dynamic	Definition commonly used in forest conservation studies. It assumes that all increases in wood extraction abroad due to policy are exported to the policy-restricted area. Due to specifics of the field and case-study, the assumption can be regarded as plausible. It should be noted that our mathematical notation disregards the so-called waste, wood imported to policy-restricted area that cannot be used. However, the waste can be significant, even 20% [32].	Meyfroidt, Lambin, 2009
[3] Net emission transfer	'Net emission transfers, which are independent of the policy and socioeconomic drivers, are often called weak carbon leakage(...)' 'We define the difference between the territorial and consumption-based emissions a 'net emission transfer (...)'. or equivalently: 'The net emission transfers represent the CO_2 emissions in each country to produce exported goods and services minus the emissions in other countries to produce imported goods and services, and are sometimes called the balance of emissions embodied in trade.'	$E_{Prod} - E_{Consum}$ which is equal to: $EEx - EEIm$	Static	In that sense, net emission transfer represents a specific amount of emissions embedded in trade, usually calculated for one year. Even if there was no change in emissions, the static definition will return a specific value. It can be expressed in absolute or relative terms, e.g. as percentage of territorial emissions.	Peters et al. 2011
[4] Change in net emission transfer		$(E_{Prod(t)} - E_{Consum(t)}) - (E_{Prod(T)} - E_{Consum(T)})$ which is equal to: $(E_{Prod(t)} - E_{Prod(T)}) - (E_{Consum(t)} - E_{Consum(T)})$	Dynamic	Since the best known definition of ('strong') CL is given in terms of emission change, 'weak' CL is often regarded also as a change but in the net emission transfers between non-mitigation and mitigation area. Thus, in a stable environment carbon leakage will be 0 in contrast to the previous static definition. The change can be given in absolute or normalized terms.	
[5] Gross emission transfer from carbon unconstrained to constrained area	'(...) alternative notion of 'weak carbon leakage', defined as the CO_2 EEI from non-Annex B countries to Annex B countries where the summation includes only non-Annex B countries. This weaker definition of carbon leakage is typically employed in the EET literature and considers the total aggregated CO_2 flows from non-Annex B to Annex B countries.'	$EEIm$	Static	This definition gives a specific amount of emissions embedded in imports from carbon unconstrained to constrained area, calculated usually for one year. Even if there was no change in emissions, the static definition will return a specific value. It can be expressed in absolute or relative terms, e.g. as percentage of territorial emissions. Theoretically, it would be also possible to construct its dynamic version (calculate the change in EEI from non-mitigation area). However, 'gross' effect is not as popular as 'net' effect in the literature on weak CL.	Peters and Hertwig, 2008
[6] Demand-driven displacement	'(...) occurs when an increase in displacement abroad is due to an increase in domestic consumption and exports of SPWP (secondary processed wood products) that remains unmatched by a corresponding increase in domestic supply, assuming unchanged policies.'	$DD = (wC'_h - we'_h) - (wC_h - we_h)$	Dynamic	Demand-driven displacement is easy to calculate when there is no environmental policy since then it represents the difference between wood consumption and production (here wood extraction). That is why sometimes authors rephrase it as weak CL. However, it should be noted that according to this definition one will have to compare current difference between wood consumption and extraction with a hypothetical one that would have occurred without environmental policy (recall no-policy-change assumption)	Meyfroidt, Lambin, 2009
[7] Total displacement	'Displacement, a more general concept than (policy-induced) leakage, is defined as a temporal, spatial, social or sectoral separation between consumption and production of a material good (...)'	$TD = PD + DD$	Dynamic	Total displacement is the sum of policy-induced leakage and demand-driven displacement. It captures the total environmental effect evoked both by policy and policy-independent economic factors. Thus, conceptually it is very similar to 'weak' CL.	Meyfroidt, Lambin, 2009

Table 2: Different definitions of leakage (-related concepts) in the literature

Introduced notation:

f: foreign country/countries without environmental policy
h: home understood as country/countries under environmental regime
t, T: different points in time
E_i: emissions in country i
E'_i: hypothetical emissions in country i
C_i: consumption in country i
P_i: production in country i (please note that in the forestry studies production corresponds to wood extraction)
wC_i: wood consumption in country i
wC'_i: hypothetical wood consumption in country i
we_i: wood extraction in country i
we'_i: hypothetical wood extraction in country i
wIm: wood imports from foreign to home
wIm': hypothetical wood imports from foreign to home
wEx: wood exports from home
wEx': hypothetical wood exports from home
E_{Prod}: territorial emissions (from production) at home
E_{Consum}: consumption emissions at home
EEx: emission embedded in exports from home to foreign
$EEIm$: emission embedded in imports from foreign to home
PD: policy-driven displacement
DD: demand-driven displacement
TD: total displacement

Remark: hypothetical refers to the scenario that would have occurred, if environmental policy at home had not been introduced.

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