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Climate policy co-benefits: a review

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ABSTRACT

Concern over mitigation costs impedes the adoption of the climate policies needed to achieve agreed global warming targets. While costs are important to consider, so are benefits. However, the evidence for climate policy co-benefits, that is, the benefits in addition to avoided climate change costs, is commonly overlooked in policy-making. In many areas, the research is limited and not comprehensively synthesised. This article counters that problem and reviews 239 peer-reviewed articles, selected from 1,749 hits from a literature search covering 'co-benefits' and related terms. Aiming to aid policy-makers and to identify research gaps, we structure, describe, analyse and synthesize the rapidly expanding knowledge on climate policy co-benefits. Improved air quality is the co-benefit category dominating the literature, but studies covering a broad geographic range also focus on diet, physical activity, soil and water quality, biodiversity, economic performance, and energy security. In these areas, co-benefits are shown to be of substantial economic value, regarding air quality often of the same order of magnitude as mitigation costs, in some instances even larger. However, the share of studies quantifying or monetizing co-benefits is limited, and the empirical evidence is small, in particular for areas besides air quality and health. Furthermore, the knowledge is seldom used in policy-making, meaning that decision-making is often biased and overly concerned with costs, leading to suboptimal climate policies and goal failures. Evidently, more research is needed, as well as improved decision-making. Understanding and acting on climate policy co-benefits can promote policies that better mitigate climate change and improve overall welfare.

Key policy insights

- Climate policy co-benefits in well-researched fields such as air quality and health are large, often equalling or exceeding mitigation costs.
- Despite their significance, co-benefits are seldom considered in decision-making, leading to biased policies and goal failures.
- In several areas, such as diet and energy security, co-benefits are sparsely researched, but emerging evidence points to high values.
- More research is needed, including on how to describe the total value of different co-benefits.
- Improved processes, documentation requirements and criteria in decision-making are needed, in order to ensure that political decision-makers consider co-benefits.

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Co-benefit; ancillary benefit; cost-benefit analysis; decision-making; synergy; climate change mitigation

1. Introduction

Despite global agreement on the need to rapidly reduce greenhouse gas (GHG) emissions and awareness of the limited carbon budget remaining to achieve mitigation objectives (IPCC, 2018; UNFCCC, 2015) climate change

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policies are often blocked by cost arguments. It is indeed important to calculate mitigation costs, but all costs and benefits associated with a policy should be analysed and considered in order to avoid distorted decision-making and goal failures (Alfredsson & Karlsson, 2016; Karlsson & Westling, 2017). However, the co-benefits of climate policy, that is, the benefits in addition to avoided climate change costs (hereafter called 'climate policy co-benefits'), are often sparsely researched, and in the areas where strong scientific evidence exists, co-benefits are commonly overlooked in policy-making (Karlsson & Westling, 2017).

Recent comprehensive reviews on co-benefits are few.¹ Gao, Kovats et al. (2018) analyse 36 articles from a literature search, but limited to public health co-benefits of climate mitigation. Mayrhofer and Gupta (2016b) study 138 articles, but primarily in a conceptual analysis, while Ürge-Vorsatz, Herrero, Dubash, and Lecocq (2014) mainly focus on taxonomic and methodological aspects. Deng, Liang, Liu, and Anadon (2018) examine over 1,500 articles, but restricted to bibliometric analysis. The broad range of peer reviewed studies on climate policy co-benefits is thus not comprehensively reviewed, to the detriment of science-based decision-making, not least since identification of these co-benefits can strengthen support for mitigating measures and allow a more complete understanding of the effects of policies (Karlsson & Westling, 2017).² With the aim of assisting policy-makers, and in order to identify research gaps, we review the existing evidence in the field, with a focus on climate change mitigation policy.³ This includes identifying, structuring, describing, analysing and synthesizing the scientific knowledge on climate policy co-benefits. The next section (2) describes material and methods, as well as concepts and categories in relation to previous reviews. This is followed by a results section (3), in which the identified studies are presented. These studies are analysed in a section (4) on cross-cutting issues. The last section (5) discusses the findings.

2. Materials and methods

This article synthesizes peer-reviewed articles in scientific journals, guided by the principles in Denyer and Tranfield (2009) and identified in Scopus based on the total search string:

(TITLE-ABS-KEY (benefit AND 'climate policy')) OR (TITLE-ABS-KEY (co-benefit OR cobenefit AND climate)) OR (TITLE-ABS-KEY ('ancillary benefits' AND climate)) OR (TITLE-ABS-KEY ('double dividend' AND climate)) OR (TITLE-ABS-KEY ('win-win' AND climate)) OR (TITLE-ABS-KEY (synergy AND 'climate policy')) AND (LIMIT-TO (LANGUAGE, 'English')) AND (LIMIT-TO (SRCTYPE, 'j'))

The resulting list of 1,749 hits (up to 30 June 2018) was delimited by exclusion of non-relevant articles based on titles or, if these were vague, abstracts. The selection was made by the authors, based on a written instruction, a rating of each article independently by all authors and a full read-through, followed by some additional rejections, eventually resulting in 239 remaining articles (see supplementary material). Collected data from each article based on 15 parameters – including category of co-benefit, how the co-benefits are quantified and monetized, policy aspects, and research gaps (see supplementary material) – provided the basis for the review.

Previous reviews categorize co-benefits differently. Gao, Kovats et al. (2018) focus on health co-benefits and divide the results into conventional sectors, e.g. energy and transportation. Mayrhofer and Gupta (2016b) divide co-benefits into five types (climate-related, economic, environmental, social and political-institutional), but the scoping of these is imprecise; e.g. 'reduce air pollution' is considered a sub-category among environmental co-benefits, whereas 'improve health' is a sub-category under social types, even though these are closely linked. It is also problematic to place 'climate-related' co-benefits on an equal basis with the other types, since these concern cases where climate mitigation is the co-benefit of a measure in another policy field (hereafter called 'climate co-benefits'), not a climate policy co-benefit. While we recognize the challenges of structuring co-benefits, and that overlaps or gaps are unavoidable, we propose a categorization with further clarity.

Our scoping focuses on climate policy co-benefits and thus excludes articles on 'climate co-benefits'. This distinction of ours, based on the 'direction' of synergy, is new. Whereas Ürge-Vorsatz et al. (2014) argue for the term 'co-impacts' and a 'multiple-objective-multiple-impact' framework (compare Obergassel, 2016), we propose a more nuanced but still straightforward three-type-taxonomy. We suggest labelling climate policy co-benefits, i.e. those covered in this review (e.g. air quality and biodiversity co-benefits) as Type 1, climate co-benefits resulting from other policy areas (e.g. GHG reductions following traffic safety measures, see Perez-Prada and Monzon

(2017)) as Type 2, and benefit synergies of policies with multiple objectives as Type 3 (e.g. Hennessey, Pittman, Morand, and Douglas, 2017). We consider this distinction user-friendly and valuable for both policy and research.

When considering potential Type 1-benefits, several perceivable categories can be identified and arranged in schemes with various layout, for example as in Figure 1, based on Alfredsson and Karlsson (2016):

The categorization in this article, however, is only partially derived from Figure 1, since studies are missing in many areas. The figure can thus be seen as a framework that is worthwhile to develop qualitatively, and to complement quantitatively, over time.

3. Results: bibliographic data and categories of climate policy co-benefits

This section starts with some bibliographic information, followed by a presentation of the reviewed articles, divided into six different categories.

The ten most frequent journals among the 239 selected articles are shown in Table 1. The range covers both natural sciences and other academic domains.

Figure 2 shows the soaring number of articles on climate policy co-benefits in recent years. Table 2 shows the most common countries for corresponding author affiliation. Regarding geographic areas targeted as study objects, Asia is the most common region for air quality articles, particularly China (22 articles). Articles spanning over more than one region are categorized as 'global'.

The most cited article is Costello et al. (2009) in *The Lancet* (960 citations), followed by Biederman and Harpole (2013) in *GCB Bioenergy* (482 citations).⁴

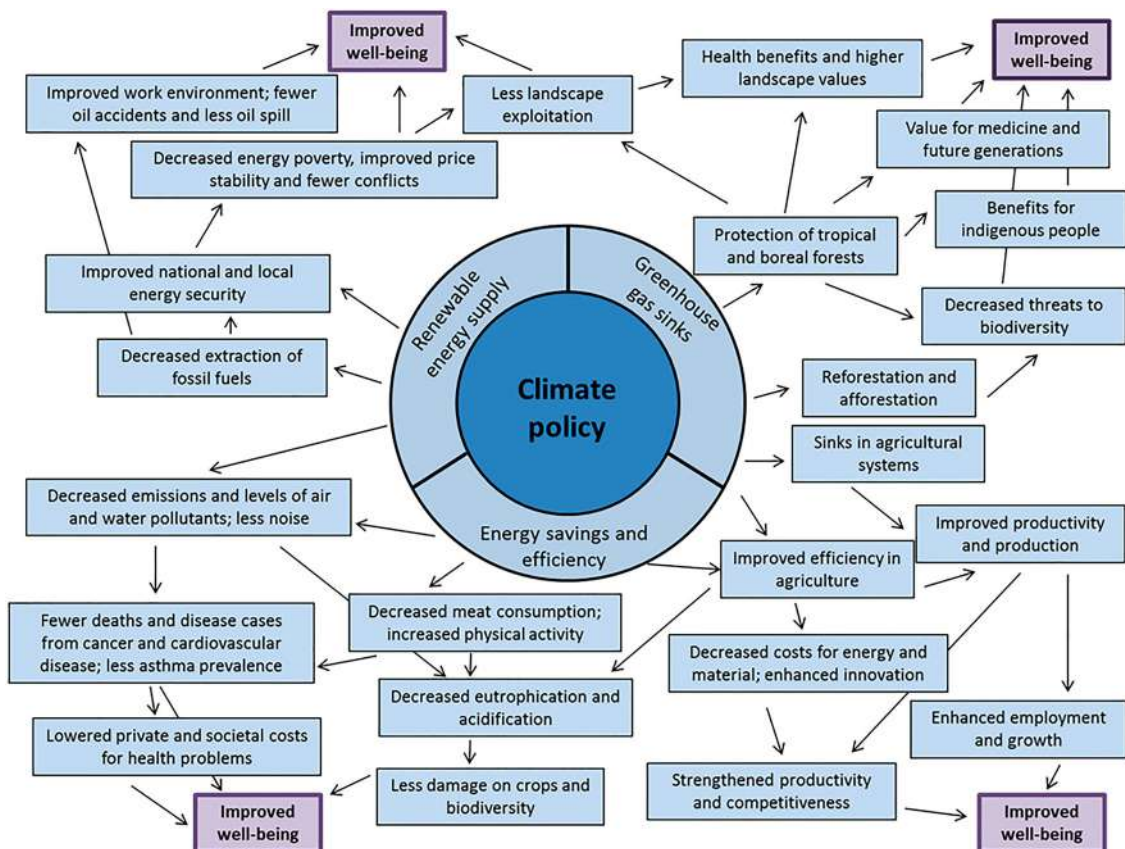


Figure 1. Co-benefit categories in climate policy. The three main components of climate policy in the circle may result in chains of potential positive effects, which – as examples – eventually may improve well-being. Developed after Alfredsson and Karlsson (2016).

Table 1. Frequent journals.

Source title (journal)	Number of articles
Energy Policy	15
Environmental Research Letters	11
Journal of Cleaner Production	10
Climate Policy	8
Climatic Change	8
Ecological Economics	8
Environmental Science and Policy	8
The Lancet	8
Environmental Science and Technology	7
Nature Climate Change	7

Categorizing articles is not straightforward, not least since many overlaps exist. Table 3 shows the six categories that will be presented in the following sections, and the number of articles under each.

3.1. Improved air quality

Air quality is by far the most studied category. A large share of the air quality-related co-benefits articles follow a certain ‘trajectory’, where each step builds on the previous one (see Figure 3). The articles referred to in this section are organized according to their final point along this trajectory. Qualitative studies on air quality co-benefits, along with review articles, are described last.

3.1.1. Quantified health effects

Health benefits have long been studied, including an early estimate by Davis (1997) that a climate policy scenario with GHG emission reductions of 10–15% would avoid 700,000 particle-related annual deaths globally by 2020, compared to business as usual.⁵ Later estimations point towards larger numbers, e.g. Anenberg et al. (2012) who state that 0.64–4.92 million deaths could be avoided annually, by implementing a set of GHG mitigation measures that simultaneously reduce PM_{2.5} and ozone. Cifuentes, Borja-Aburto, Gouveia, Thurston, and Davis (2001) estimate that, in just the four cities New York, Mexico City, Sao Paulo and Santiago, 18,000–116,000

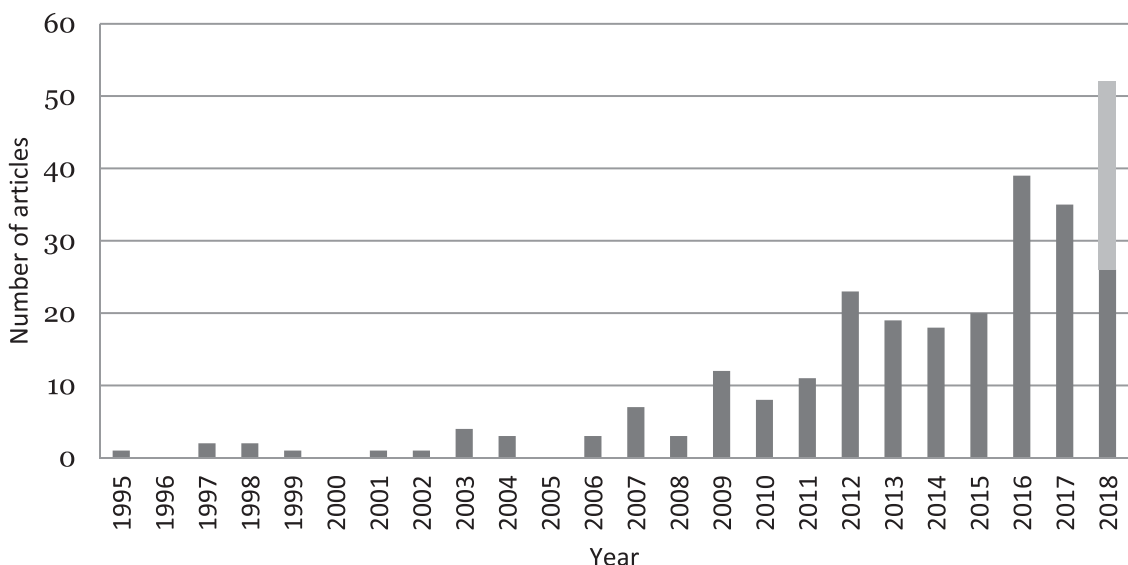


Figure 2. Number of articles over time. Note that the article search only covered the first half of 2018 (dashed part of the bar illustrates the same number of articles for the second half of 2018).

Table 2. Corresponding author countries.

Country	Number of articles
USA	55
UK	23
China	20
Germany	12
Netherlands	11
Australia	10
Austria	10
Norway	8
Japan	7
Denmark	6
Canada	6
Spain	6

Table 3. Co-benefit categories in section 3 of this article, and number of reviewed articles sorted under each. The remaining 23 reviewed articles are included in sections 2 and 4 in this article.

Category	Number of articles
Improved air quality	122
Improved diet and physical activity	16
Improved soil and water quality	16
Improved biodiversity	21
Improved economic and organizational performance	34
Improved energy security	7

premature deaths could be avoided over two decades, besides adding 37 million person-days of work, due to the health improvements of better air quality. Other articles quantify particle levels without linkages to quantified health improvements (Braspenning Radu et al., 2016; Rao et al., 2016; Singh, Strømman, & Hertwich, 2012).

Several estimations concern air pollution in Asia (Dhar & Shukla, 2015; Dhar, Pathak, & Shukla, 2017; Tan, Wen, & Chen, 2016; Yang & Teng, 2018; Zhang, Worrell, & Crijns-Graus, 2015; Zhao, Ma, Dong, & Jiang, 2017). According to van Vliet et al. (2012), improved outdoor air quality could save up to 1.82 million lives annually in Asia. Studying emission reduction scenarios for China, Peng, Yang, Wagner, and Mauzerall (2017) find that increasing industrial energy efficiency by 10% would reduce GHG emissions by 440 Mt CO₂e while improving air quality and saving 27,000 lives annually. There is special emphasis on urban Asia, notably on mega-cities like Delhi (Bhanarkar et al., 2018; Garg, 2011), Beijing (Liu et al., 2013), Ahmedabad (Pathak & Shukla, 2016), Hanoi (Kim Oanh, Thuy Phuong, & Permadi, 2012), Kuala Lumpur (Kwan, Tainio, Woodcock, & Hashim, 2016; Shakya, 2016), Kathmandu (Shakya, 2016; Shakya & Shrestha, 2011; Shrestha, Kim Oanh, Xu, Rupakheti, & Lawrence, 2013) and others (Liu, Huang et al., 2017; Liu, Liao, Lin, Li, & Zeng, 2017; Mittal, Hanaoka, Shukla, & Masui, 2015; Ren et al., 2012; Zheng, Jiang, Qiao, Zhu, & Kennedy, 2016; Zhou, Yabar, Mizunoya, & Higano, 2017). Somewhat unconventionally, Liu et al. (2016) use survey data to find that some GHG mitigation strategies may increase citizens' subjective wellbeing, partly due to better air quality.

Several studies show potential air quality co-benefits in Europe, including in the UK and Ireland (Alam, Hyde, Duffy, & McNabola, 2017, 2018; Wilkinson et al., 2009) and the Nordic countries (Åström, Tohka, Bak, Lindblad, & Arnell, 2013; Williams, 2007). Williams et al. (2018) estimate the life-years saved in different scenarios for meeting

**Figure 3.** Trajectory of quantifications.

UK climate targets, where reliance on biomass is the scenario that reaches the target with the least beneficial effect on air quality. Rafaj, Cofala, Kuenen, Wyrwa, and Zyśk (2014) associate large potential co-benefits in Europe with renewable energy, due to reduced mercury emissions to air. Large potentials for reaping air quality co-benefits are also shown for several European cities, e.g. Rotterdam (Tobollik et al., 2016) and Barcelona, Malmö, Sofia and Freiburg (Creutzig, Mühlhoff, & Römer, 2012).

Several studies quantify air quality and health improvements due to potential US climate policy (Fullerton & Karney, 2018; Zhang, Wang, Yahya, Campbell, & Jena, 2016). Creutzig et al. (2012) estimate 3,500 avoided deaths in the US in a scenario that stretches to 2020. Driscoll et al. (2015) and Zhang, Bowden et al. (2016) study reduced emissions of PM_{2.5} and ozone in the US and consequential health benefits. The latter compares the impact of domestic and international mitigation measures and finds that ozone pollution in the US is reduced more by measures in other countries. Some studies show significant air quality co-benefits in South Africa, not least in the road transport sector (Klausbrückner, Annegarn, Henneman, & Rafaj, 2016; Thambiran & Diab, 2011a, 2011b). Finally, in an empirical study, Shaw, Hales, Edwards, Howden-Chapman, and Stanley (2018) show how air quality is improved by fuel price increases in New Zealand.

3.1.2. *Economic valuations*

In a global modelling study, Xie, Weng, and Cai (2018) state that Integrated Assessment Models that disregard co-benefits 'inevitably underestimate the real benefits of climate mitigation'. The authors show that adding nitrogen oxides (NO_x) to the model changes optimal abatement policy, and indicate that including additional pollutants would ameliorate the model. One global estimation indicates air pollution control savings of approximately EUR 250 billion annually by 2050, compared to a case without climate measures (Rafaj, Schöpp, Russ, Heyes, & Amann, 2013). Focusing on black carbon, Rypdal et al. (2009) find that mitigation costs are lowest and air quality co-benefits are largest in Asia. Studying the aviation industry, Dorbian, Wolfe, and Waitz (2011) estimate the costs of GHG emissions, as well as the costs of air pollution, and find that air pollution from aviation represents a significant damage cost, valued at up to the same magnitude as the damage cost of aviation's GHG emissions (depending on assumptions and choice of metrics). In one of few backward-looking studies, green buildings⁶ are estimated to have provided USD 13.3 billion (9.8–16.6) in benefits between 2000 and 2016 in the US, China, India, Brazil, Germany and Turkey due to energy savings but also due to reduced air pollution (MacNaughton et al., 2018).

Several Asian studies estimate the GDP-effects of a carbon tax. Adding monetized co-benefits values, two studies show that a carbon tax enhances welfare (Aunan et al., 2007; Li, 2006), whereas one shows that GDP is reduced by the tax, but less so due to co-benefits (Li, 2002). Ma et al. (2013) estimate that the air quality co-benefits of wind power alone are worth 0.46% of GDP in the Xinjiang region in Northwest China.

Several studies focus on Europe. Apsimon, Amann, Åström, and Oxley (2009) show that achieving the EU's Climate and Energy Package by 2020 could reduce air pollution control costs by EUR 8.5 billion annually.⁷ According to Schwanitz, Longden, Knopf, and Capros (2015) air quality and energy security co-benefits of climate policy could motivate immediate mitigation. Vandenberghe and Albrecht (2018) conclude that improved air quality and dietary changes in Belgium could save 0.6–1.1% of total health care expenditures. Sargiannis et al. (2017) show co-benefits of transport-related emissions in Thessaloniki worth EUR 150–162 million annually by 2020. See also Rypdal et al. (2007) for estimated savings in the Nordic countries.

Zapata, Muller, and Kleeman (2013) estimate that 560–1100 premature deaths, valued at USD 5.4 billion, are avoided annually due to Californian climate legislation. According to Buonocore, Luckow, Fisher, Kempton, and Levy (2016), offshore wind power on the US East Coast produces health and climate benefits worth USD 54–120/MWh. Wiser et al. (2016) show that increasing solar energy in the US to 14% of the nation's electricity by 2030 and 27% by 2050, could provide air quality and health co-benefits over the period 2015–2050 estimated at a net present value of USD 77–298 billion.

3.1.3. *Economic valuations compared to mitigation cost*

Some articles compare monetary valuations of co-benefits to mitigation costs, as percentage of mitigation costs or USD/tCO₂e. The latter articles, which provide monetary estimates that are easier to compare across policy fields and geographies, are summarized in table 4.

Table 4. Monetary estimates of air quality co-benefits in a single, comparable, metric.

Article	Monetary value (USD/ tCO ₂ e)	What is valued
Balbus et al. (2014, erratum)	40–93 USD/tCO ₂ e	US, health benefits due to PM _{2.5} reduction.
Burtraw et al. (2003)	12–14 USD/tCO ₂ e	US, health benefits due to NO _x reductions and savings on NO _x and SO ₂ abatement.
Crawford-Brown et al. (2012)	20 USD/tCO ₂ e	Mexico, health benefits due to ozone and PM reductions.
Garcia-Menendez et al. (2015)	45–209 USD/tCO ₂ e	US, health benefits due to ozone and PM reductions.
Joh et al. (2003)	6.8–7.5 USD/tCO ₂ e	South Korea, health benefits due to PM reductions.
Krook Riekkola et al. (2011)	3.9–32.1 EUR/tCO ₂ e	Sweden, health (and other) benefits of NO _x , NMVOC, PM _{2.5} and SO ₂ reductions.
Levy et al. (2016)	12–390 USD/tCO ₂ e	US, value includes both climate and health benefits
Saari et al. (2015)	2–14 USD/tCO ₂ e	US, health benefits due to PM reduction.
Ščasný et al. (2015)	15.5–17 EUR/tCO ₂ e	Europe, health (and other) benefits of reductions of 10 pollutants.
Thompson et al. (2016)	80–148 USD/tCO ₂ e	Northeast US, health benefits due to ozone and PM reductions.
Vennemo et al. (2006)	>6 USD/tCO ₂ e	China, health (and other) benefits due to PM and SO ₂ reductions following energy CDM projects.
West et al. (2012)	13–17 USD/tCO ₂ e	Global, health benefits due to ozone reductions of methane-reducing policies.
West et al. (2013)	70–840 USD/tCO ₂ e	Global, health benefits due to PM and ozone reductions.
Woollacott (2018)	31 USD/tCO ₂ e	US, health benefits due to PM reductions.
Yang et al. (2013)	3–39 USD/tCO ₂ e	China, health (and other) benefits due to PM, NO _x and SO ₂ reductions following abatement measures in the cement sector.
Zhang et al. (2017)	45–137 USD/tCO ₂ e	US, health benefits due to ozone and PM _{2.5} reductions.

Globally, air quality co-benefits are estimated at approximately 75% of mitigation costs (Andersen, 2017; Bollen, 2015). Among regional comparisons, West et al. (2013) estimate air quality co-benefits by using value of statistical life and find the largest co-benefits in China (USD 70–840/tCO₂), and slightly lower in Europe and the US. Markandya et al. (2009) conclude that health benefits outweigh mitigation costs in India but not in China or the EU, due to both lower mitigation costs and higher co-benefits in India. However, Markandya et al. (2018) find that air quality co-benefits significantly outweigh policy costs in all scenarios for India and can do so for China as well, under certain assumptions. In some mitigation strategies, the median co-benefit is twice as high as the median cost, globally. They find that pursuing the 1.5°C target instead of the 2°C target would generate a substantial net benefit in India, and could do so in China and the EU as well, depending on value of statistical life assumptions. Robinson (2014) finds that India and Australia can benefit from so-called ‘no-regret’ climate measures, where the value of co-benefits outweighs mitigation costs.

West, Fiore, and Horowitz (2012) estimate that the value of methane-reducing policies would create air quality co-benefits worth USD 13–17/tCO₂e globally. McCollum et al. (2013) calculate that air quality together with energy security co-benefits could reach 0.1–0.7% of global GDP in 2030.

Partridge and Gamkhar (2012) study replacing coal with renewables in China and find co-benefits corresponding to 10% or less of the cost. Several others, however, find huge benefits, e.g. Li et al. (2018), who show that the cost of China’s pledge to peak CO₂ emissions by 2030 can be fully offset by air quality health co-benefits. Several other Asian studies conclude that air quality co-benefits cover more than the entire cost of certain mitigation policies and measures (Aunan, Fang, Vennemo, Oye, & Seip, 2004; Cai et al., 2018; Li & Crawford-Brown, 2011; Xing, Hanaoka, Kanamori, & Masui, 2016). The study on GHG mitigation in the Chinese cement sector by Yang, Teng, and Wang (2013) finds a co-benefit value of USD 3–39/tCO₂. Joh, Nam, Shim, Sung, and Shin (2003) find that modest GHG reductions can create co-benefits worth USD 6.8–7.5/tCO₂ in South Korea and Vennemo et al. (2006) calculate co-benefits over USD 6/tCO₂ from energy projects in China.

Several European studies also find that air quality co-benefits offset a large proportion of climate policy costs. Schucht et al. (2015) estimate at least 85% of mitigation costs to be covered by co-benefits from decreased particle and ozone levels. Ščasný, Massetti, Melichar, and Carrara (2015) estimate Europe-wide values for the reduction of air pollution in a carbon tax scenario to EUR 15.5–17/tCO₂ (up to approximately three times higher, depending on discount rate). Krook Riekkola, Ahlgren, and Söderholm (2011) find that Swedish climate policy produces health co-benefits of EUR 3.9–32.1 per tCO₂. According to van Vuuren et al. (2006), air quality co-benefits of achieving Europe’s Kyoto Protocol targets would cover around 50% of policy costs, whereas Aaheim, Kristin, and Seip (1999) conclude health benefits of better air quality in Hungary to be large enough to cover almost 90% of the country’s cost of complying with the Kyoto Protocol. Besides the cost of

health effects, governments can save up to a few percent of climate policy costs on reduced pollution control (Markandya & Rübbelke, 2004; Rive, 2010).

Several US studies find air quality co-benefits values of USD 8–125/tCO₂ (Burtraw et al., 2003; Garcia-Menendez, Saari, Monier, & Selin, 2015; Levy et al., 2016; Woollacott, 2018; Zhang, Smith, Bowden, Adelman, & West, 2017) (see also Balbus, Greenblatt, Chari, Millstein, & Ebi, 2014, erratum). Thompson, Rausch, Saari, and Selin (2016) estimate co-benefits of reduced particles and ozone at USD 80/tCO₂ in a scenario with clean energy standards for the electricity sector, and up to USD 148/tCO₂ in an economy-wide cap-and-trade scenario with equal amount of emission decrease, covering 185% or 844% respectively of each scenario's policy costs. Estimates vary depending on scenarios, methodologies and pollutants included. For example, Saari, Selin, Rausch, and Thompson (2015) find reduction of fine particulate matter alone being worth USD 2–14/tCO₂.

Muller (2012) reports costs of 'co-pollutants', e.g. USD 87/tCO₂ from a coal-fired power plant, and USD 12/tCO₂ for a light duty diesel-powered vehicle. Since the location of an emission source influences the cost of the co-pollutant, optimal policy design varies between urban and rural areas and the US east coast tends to benefit more due to wind patterns. For Mexico, one study estimates co-benefits at approximately USD 20/tCO₂ (Crawford-Brown, Barker, Anger, & Dessens, 2012). Dessus and O'Connor (2003) find that even under conservative assumptions, CO₂ emissions could be reduced by 20% without welfare loss in Santiago de Chile, due to co-benefits.

3.1.4. Qualitative studies and review articles

Several qualitative studies on air quality co-benefits argue for further analysis (Jiang et al., 2013; Richardson, English, & Rudolph, 2012; Rowlands, 2011; Teng & Jotzo, 2014), dissemination of results (Wagner, 2012) and interdisciplinary approaches (Zusman et al., 2013). Labriet, Caldés, and Izquierdo (2009) conclude that the Clean Development Mechanism under the Kyoto Protocol potentially could deliver improved air quality and other co-benefits. Roberts (2009) considers that health professionals have an 'urgent responsibility' to educate policy-makers and others on these matters, which is also in line with the findings by Dhar, Macmillan, Lindsay, and Woodward (2009). Harlan and Ruddell (2011) as well as Milner, Davies, and Wilkinson (2012) study air quality co-benefits from an urban perspective, the former arguing that city studies are most actionable when they concern specific cities and cases (see also Sabel et al. (2016)).

Several review articles concern air quality co-benefits (Bell et al., 2008; Gao, Kovats et al., 2018; Haines et al., 2007; Jack & Kinney, 2010; Williams, 2012). Two that focus on transportation (Kwan & Hashim, 2016; Shaw, Hales, Howden-Chapman, & Edwards, 2014) find substantial co-benefits in air quality, but also regarding noise reduction and traffic safety. Nemet, Holloway, and Meier (2010) find economic values of air quality co-benefits in 37 studies ranging from USD 2–196/tCO₂.

3.2. Improved diet and physical activity

The review by Yip, Crane, and Karnon (2013) of seven quantitative studies on co-benefits of reduced meat consumption points out possible parallel reductions of emissions (–3 to –30%) and disease burden (–1 to –16%). A review by Quam, Rocklöv, Quam, and Lucas (2017) similarly illustrates that health co-benefits follow reduced meat consumption and decreased emissions. Reviewing ancillary health effects in air quality, transportation and diet studies, Chang et al. (2017), include six assessments of reduced intake of red meat and even though methods differed, all scenarios yield considerable parallel health and climate benefits. The most well-developed of these six studies, Springmann, Godfray, Rayner, and Scarborough (2016), concludes that a transition towards plant-based diets could reduce global mortality 6–10% and food-related GHG emissions 29–70% by 2050, compared with a reference scenario, equalling health co-benefits of 0.4–13% of global GDP. In a study by Farchi, De Sario, Lapucci, Davoli, and Michelozzi (2017) of three regional Italian meat reduction scenarios, 2.3–4.5% fewer deaths in colorectal cancer and 2–4% fewer deaths in cardiovascular diseases are associated with clear GHG emission reductions (263 kg CO₂e/yr and person). These various findings support the statement of Watts et al. (2017) in 'The Lancet Countdown project' that climate policy health co-benefits provide 'a powerful incentive to accelerate policy change, as these benefits are experienced in the near term ...' One suitable policy instrument here could be a global meat tax, as proposed by Jarka, Tinggaard, and Tomas (2018), or national

carbon taxation. In a modelling study for Belgium in 2015, the latter instrument reduces GHG emission by 4.5–8.7% in the food sector and prevents 42–79 000 disability-adjusted life years (DALYs), saving hundreds of millions of Euros (Vandenberghe & Albrecht, 2018).

Regarding physical activity, Jensen et al. (2013) conclude that, among various strategies for achieving UK 2030 climate targets, increased active travel gives important, net positive, health co-benefits. Wolkinger et al. (2018) analyse three mobility scenarios in three larger Austrian cities and show substantial GHG emission reductions along with increased physical activity and reduced annual direct and indirect health costs up to 10 million Euros (intangible costs uncounted). In a modelling study covering Auckland, New Zealand, over 40 years, physical separation on main roads and speed reduction on local streets yield co-benefits 10–25 times greater than costs of e.g. investments (Macmillan et al., 2014). An empirical analysis of several active travel interventions (for e.g. walking and cycling) in two provincial cities in New Zealand also shows clear parallel reductions in diseases and emissions, amounting to a benefit cost ratio of 11:1 (Chapman et al., 2018). Similar co-benefits of increased cycling are described for Australia (Rissel, 2009). An empirical study on a transport energy index (energy burned by walking, related to energy burned in motorized transportation) shows that residential and intersection density as well as transit accessibility are associated with increased walking, bringing benefits for both health and the climate (Frank, Greenwald, Winkelmann, Chapman, & Kavage, 2010). Patz, Gibbs, Foley, Rogers, and Smith (2007) point out multiple co-benefits of sustainable urban design and the ‘triple-win’ that can be gained from replacing car trips by biking or walking, including enhanced personal fitness and improved air quality in addition to reduced GHG emissions. Lowe (2014) identifies potential co-benefits and policy-proposals in Australia for active transport, improved diets, and macro-level policies.

3.3. Improved soil and water quality

In a review, Verspecht, Vandermeulen, Ter Avest, and van Huylenbroeck (2012) propose a framework for clarifying trade-offs and co-benefits from climate mitigation in agriculture. Dumanski (2004) discusses the relationship between soil conservation, carbon sequestration and emission targets under the Kyoto Protocol and concludes that a win-win situation exists. Lal, Follett, Stewart, and Kimble (2007) estimate the potential of improved farming practices that increase the soil carbon pool and Lal (2010a, 2010b) calculates that atmospheric CO₂ levels can be reduced by 50 ppm by the end of the twenty-first century in parallel with producing significant co-benefits in terms of increased above ground productivity. Luo et al. (2017) model Australian rain-fed wheat systems and show that site-specific best nitrogen management can increase yield by 76% while reducing soil CO₂ and nitrogen dioxide emissions. In 403 on-farm trials across China, An et al. (2015) find that a combination of best farming practice and improving soils could increase rice production by 18% while reducing nitrogen fertilizer consumption by 22% and decreasing GHG emissions by 7%. A review of 371 studies shows that biochar can promote e.g. carbon storage, increased above-ground productivity and crop yield (Biederman & Harpole, 2013). Moreover, crushing and adding carbon-binding and fertilizing silicate minerals (enhanced rock weathering) to arable land creates carbon sinks and may improve food security (Beerling, 2017). Furthermore, a choice experiment in Australia shows larger willingness to pay for carbon-sequestering farming when associated with co-benefits in terms of increased area of native vegetation, but shows no support for practices that reduce soil erosion, which is less well-known (Kragt, Gibson, Maseyk, & Wilson, 2016).

Five studies concern water quality but only as one of several co-benefits. Singh et al. (2012) show that scenarios with carbon capture and storage (CCS) are associated with less increase in eutrophication than in a base scenario without CCS. Ojea, Loureiro, Alló, and Barrio (2016) estimate co-benefits from forest ecosystem services in REDD⁸ and non-REDD countries. The air quality and water regulation co-benefits are on average valued at USD 1,541/ha and year in non-REDD countries and USD 5,790/ha and year in REDD-countries. Torres, Macmillan, Skutsch, and Lovett (2015) explore forest carbon offsets in voluntary carbon markets in Mexico and show that citizens willingly pay more for offsets closer to home, as proximate forests provide a range of co-benefits, including local water regulation. Moreover, renewable electricity production performs better than fossil fuel-based electricity on several environmental parameters, including decreased water depletion and freshwater toxicity (Bergesen, Heath, Gibon, & Suh, 2014; Gibon, Arvesen, & Hertwich, 2017; Gibon, Hertwich, Arvesen, Singh, & Veronesi, 2017).

3.4. Improved biodiversity

Biodiversity co-benefits stem from, for example, reduced deforestation, afforestation and improved forest management. The monetary value of these is not calculated in the reviewed studies but rough estimates are given. Plantinga and Wu (2003) conclude that the value of reduced soil erosion and enhanced wildlife habitat from afforestation in Wisconsin (US) is of the same magnitude as the costs of the associated carbon sequestration policy. Rodríguez-Entrena, Espinosa-Goded, and Barreiro-Hurlé (2014) find that co-benefits motivate 50% of the willingness to pay for carbon sequestration policies in Andalusia (Spain), and Beaudrot et al. (2016) that more wildlife diversity and carbon stock conservation can be achieved for the same budget if both objectives are pursued in tandem. The latter is concluded based on 80 REDD+ projects. A subset of studies explicitly analyses REDD and REDD+ policies (Busch, Godoy, Turner, & Harvey, 2011; Magnago et al., 2015; Panfil & Harvey, 2016; Pichancourt, Firn, Chadès, & Martin, 2014; Simonet, Delacote, & Robert, 2016; Stickler et al., 2009; Strassburg et al., 2010; Strassburg et al., 2012), in which synergies between carbon storage and biodiversity protection are pointed out, as well as socio-economic co-benefits. Several studies, however, find that top-ranking carbon stock sites do not necessarily coincide with high biodiversity (Dwyer, Fensham, Butler, & Buckley, 2009; Greve, Reyers, Mette Lykke, & Svenning, 2013; Siikamäki & Newbold, 2012; Strassburg et al., 2010). Several studies thus call for careful policy design in order to realize co-benefits efficiently (Beaudrot et al., 2016; Bryan et al., 2016; De Beenhouwer et al., 2016; Greve et al., 2013; Panfil & Harvey, 2016; Pichancourt et al., 2014; Stickler et al., 2009; Strassburg et al., 2010; Wüstemann et al., 2017). Essl, Erb, Glatzel, and Pauchard (2018) even claim that recognizing the risk for 'bio-perverse impacts of climate policies on biodiversity' is crucial for the success of climate change mitigation. Anderson, Field, and Mach (2017) evaluate California's forest offset programme and find that it provides additional emission reductions and additional conservation co-benefits in terms of water quality, recreation and wildlife. In Colombia, natural forest regeneration may accumulate carbon while supporting local communities more than e.g. cattle production (Gilroy et al., 2014).

3.5. Improved economic and organizational performance

Most articles analysing co-benefits in terms of improved economic performance focus on the existence of a double dividend, i.e. improved economic efficiency when environmental tax revenues are used to reduce distortionary taxes. Early studies indicate some support for this theory (Proost & Van Regemorter, 1995; Stephan & Muller-Furstenberger, 1998) and later research confirms a double dividend for a variety of climate policies in different regions. Landa Rivera, Reynès, Islas Cortes, Bellocq, and Grazi (2016) find that a proposed Mexican energy policy would reduce CO₂ emissions by 75%. Full redistribution of carbon tax revenues gives a double dividend, making the policy beneficial in terms of both GDP and reduced CO₂ emissions. Chang (2014) finds that an electricity tax increases social welfare in Taiwan, and Jakob (2018) concludes that emphasis on co-benefits can promote human development and enhance support for carbon pricing in Peru. Yahoo and Othman (2017) find that a carbon tax in conjunction with revenue-recycling provides a double dividend and leads to welfare enhancements, while stepping up the production of renewable energy. A review by Siegmeier et al. (2018) similarly concludes that climate policy, even under a 1.5°C target, may substantially support fiscal objectives and lower mitigation costs. Suckall, Stringer, and Tompkins (2014) find that climate compatible development is increasingly employed by international donors and policy-makers seeking 'triple-wins' for development, adaptation and mitigation, but that these are likely under-reported. Leimbach, Roming, Schultes, and Schwerhoff (2018) conclude that stringent global climate policies may allow Sub-Saharan African countries to implement 2°C policies at around net zero costs, thanks to e.g. increased biomass export and international financial support.

Barbier (2014) and Colenbrander et al. (2017) review impacts on poverty from climate policy, but find both direct and indirect effects that either reduce or worsen poverty, so the results are far from conclusive. A few articles study employment co-benefits and these also show mixed results (Chateau & Saint-Martin, 2013; Laitner, Bernow, & Decicco, 1998; Pollitt, Alexandri, Chewpreecha, & Klaassen, 2015; Yamazaki, 2017). Pollitt et al. (2015) conclude that the employment impacts of future EU climate policies stem from the large investments needed to meet the combined targets of reducing GHG emissions, increasing supply from renewables

and improving energy efficiency. Yamazaki (2017) empirically analyses British Columbia's revenue-neutral carbon tax, finding falling employment in the most carbon-intensive and trade-sensitive industries, while the opposite is seen in clean service industries, with a small but statistically significant 0.74% net average annual increase in 2007–2013.

Another economic co-benefit is reduced costs for energy. Bach (1997) finds huge potential gains in Münster, Germany from implementing energy efficient technology leading to reduced costs for consumers and city utilities. The calculated benefits and losses for 1996–2021 show favourable payback times of 11–14 years for the total commercial sector and 2–5 years for individual investment objects and projects. Dowling and Russ (2012) find that the costs of reaching even ambitious emission reduction targets are offset by significant co-benefits, including reduced energy import bills. Oshiro, Kainuma, and Masui (2016) find that deep decarbonization in Japan by 2050 is technically feasible – even without nuclear power – and could contribute to reduced costs for fossil fuel imports of around 70%. MacNaughton et al. (2018) show that energy efficient buildings in six countries saved USD 7.5 billion in energy costs between 2000 and 2016. Fine, Busch, and Garderet (2012) analyse climate policies in California in terms of the value of reduced exposure to gasoline and diesel price spikes. They estimate the annual upside potential value at USD 2.4–5.2 billion (2007 dollars). Kim et al. (2018) analyse industrial and urban symbiosis in Korea, finding a potential reduction of 243,396 tCO₂/year, saving USD 48 million in fuel costs yearly.

Several articles analyse co-benefits of efficient cook-stoves in developing countries, e.g. fuelwood savings, reduced deforestation, stronger local economies, higher income, improved health and environmental conservation (Anenberg et al., 2013; Aung et al., 2016; Dagnachew, Lucas, Hof, & van Vuuren, 2018; Freeman & Zerriffi, 2012; García-Frapolli et al., 2010; Rowlands, 2011; Simon, Bumpus, & Mann, 2012; Zhang & Wang, 2011). The benefits (including co-benefits) of improved biomass cookstoves in Mexico are about ten times higher than the associated costs, with the largest contributions from fuelwood savings (53%) and reduced health impacts (28%) (García-Frapolli et al., 2010). Zhang and Wang (2011) show that benefits of improved cook-stoves in rural Mexico outweigh costs 4–9 times when co-benefits are considered. Wathore, Mortimer, and Grieshop (2017) show that indoor emissions decrease when households in rural Malawi use efficient cook-stoves. In rural India, efficient cook-stoves reduce black carbon concentrations by 40% (Patange et al., 2015).

Kalafatis (2018) finds co-benefits in terms of overlaps with economic development from climate policy in a survey covering 287 cities in the US. Maisonnave, Pycroft, Saveyn, and Ciscar (2012) study a unilateral EU approach and show that GDP decreases more under rising oil prices in the absence of climate policy than in the presence of it, thereby illustrating macro-economic protection as a co-benefit. Besides strict economic effects, carbon management may foster co-benefits of an organizational nature. Birchall (2014) shows empirically that a New Zealand local government climate programme, which led to clear emission reductions, also promoted inter-council collaboration, awareness and learning.

3.6. Improved energy security

Energy security co-benefits are potentially large (Mignone, 2007) but studies are few and seldom define the concept. In one study, van Vliet et al. (2012) describe energy security by help of three indicators: energy imports, diversity of primary energy supply and a compound indicator combining the two former indicators. When modelling energy systems in three Asian regions (CPA, SAS and PAS⁹), they conclude that stringent climate policies improve supply diversity and the compound indicator in all three regions. They find that co-benefits and lowered costs largely offset the doubling of investments in energy systems by 2030 that they assume is needed to achieve climate objectives. Similarly, modelling of carbon taxation by Duan and Wang (2018) shows significant energy security co-benefits for China in terms of reduced energy intensity, expenditure and per capita consumption. A Europe-centred modelling of fossil fuel import dependency, associated costs and energy diversity indicators, concludes that oil imports decrease by 46–54% in all models and climate policy scenarios, between 2010 and 2050, compared to 29% in the base scenario (Schwanitz et al., 2015).

In a study on energy planning in Kathmandu, Shakya (2016) concludes that all low carbon scenarios studied show improved energy security, with the largest in the transport sector and the lowest in agriculture. A study on

passenger transport in Ahmedabad demonstrates that a low carbon scenario delivers development co-benefits in terms of 47% reduced energy demand, improved energy security and improved air quality (Pathak & Shukla, 2016). In an analysis of the role of energy efficiency in six no-policy and climate policy scenarios for India, Chaturvedi and Shukla (2014) show co-benefits in terms of substantially decreased energy imports.

4. Cross-cutting analysis

In the following, the results described above are analysed from a set of cross-cutting perspectives.

4.1. Conceptual development

Among the reviewed articles, the concept of ‘co-benefit’ first appears in 2003, after ‘ancillary benefits’ in 2001 and ‘double dividend’¹⁰ in 1995 (see Figure 4 that also shows some related concepts). Since 2009, ‘co-benefits’ has been the most common concept, in particular explored for air quality issues. The Intergovernmental Panel on Climate Change (IPCC) previously distinguished between side effects specific to climate change policy (ancillary benefits) and side effects of any policy (co-benefits) but more recently, the IPCC (2018) has used ‘co-benefits’ for both, defined as: ‘The positive effects that a policy or measure aimed at one objective might have on other objectives, thereby increasing the total benefits for society or the environment’.

Among academic analyses, Mayrhofer and Gupta (2016b) and Ürge-Vorsatz et al. (2014) consider the co-benefit concept to lack clearly identifiable boundaries. This review confirms this and in addition shows that most scholars do not define the concept at all. Ürge-Vorsatz et al. (2014) conclude that the co-benefit concept is generally considered as positive and Mayrhofer and Gupta (2016b) identify a change from a negative (‘no regrets’) or limited (‘double dividend’) framing, to a positive one (i.e. co-benefits). They view this as advantageous but also that it may lead to a positive normative bias with disregard of negative outcomes.

One major attraction of including climate policy co-benefits in e.g. cost–benefit analysis (CBA) is that subsequent decision-making becomes more balanced, but it also helps to cope with the ‘wicked problem’¹¹

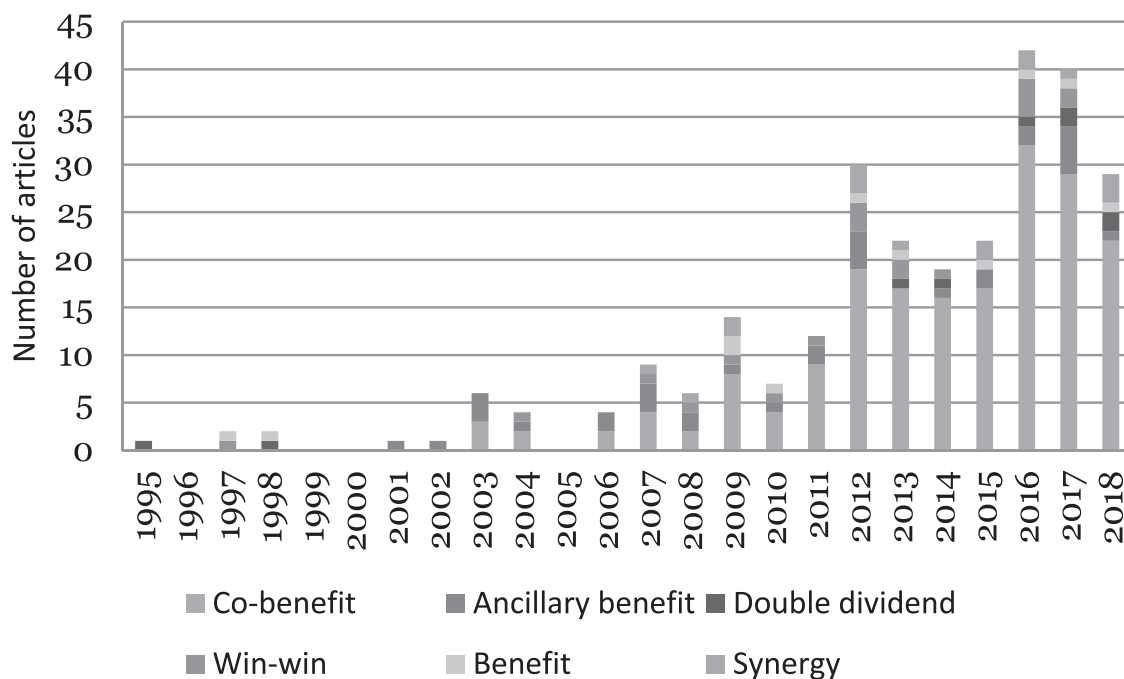


Figure 4. Conceptual development.

linked to climate policy, with benefits viewed as long-term and globally dispersed, but costs as short-term and local. Most co-benefits, however, are also close in space and time (Mayrhofer & Gupta, 2016b), so visualizing them may increase the willingness to pay for climate policy (Torres et al., 2015), and frame policies more correctly, in a way that may resonate with local political priorities (Shaw et al., 2014) and with views among indigenous organizations (Robinson et al., 2016). While climate mitigation is often costly for developing countries, integration with other national priorities may increase resources for policies (Mayrhofer & Gupta, 2016a). Evidently, identifying co-benefits can facilitate decision-making (Bain et al., 2016).

However, risks are also pointed out. The co-benefit approach is claimed to often be linked to incremental measures, which do not address root causes of climate change (Mayrhofer & Gupta, 2016b; Puppim De Oliveira et al., 2013). Dubash, Raghunandan, Sant, and Sreenivas (2013) see a risk that co-benefits thereby motivate opportunistic policies. The positive epistemology underlying the concept, indicating an apolitical, technocratic and neutral context, may prevent considering political realities (Mayrhofer & Gupta, 2016b), which in case studies by Oliveira and Thorseth (2016) may be linked to e.g. inequality. Moreover, if the commonly larger co-benefits for people living under poor conditions misdirect policies towards developing countries, this could be seen as expressing environmental imperialism (Mayrhofer & Gupta, 2016b). Despite goal synergies, Hildingsson and Johansson (2016) consequently point out a need for ‘flanking policies’ against unintended consequences. Since the primary policy objectives are not necessarily known, and since effects that are positive for one stakeholder may be negative for another, the neutral term ‘co-impact’ is moreover proposed by Ürge-Vorsatz et al. (2014).

In summary, the co-benefit concept is gradually gaining ground, but further clarity on the interpretation of the concept is needed. Scholars should describe how they use and define the co-benefit concept in their analysis. The IPCC’s definition could be applied, complemented with our taxonomy, to clarify whether co-benefits are Type 1, Type 2 or Type 3. Although the proposed co-impact concept is neutral, it has received little attention and using it risks counteracting the increasing conceptual convergence.

4.2. Qualitative, quantified and monetized results

CBA is, despite many shortcomings (van den Bergh, 2017), commonly playing an important role in climate policy development. Quantification and particularly monetization of co-benefits is therefore indeed policy-relevant.

When categorizing all reviewed articles as qualitative or quantitative, and separating the latter into quantified physical effects, quantified monetary effects, and monetary effects compared to mitigation costs, a large variation in how quantitative results are presented becomes obvious (Figure 5). On a more detailed level, this includes avoided deaths, percentage of mitigation costs, and monetary value per ton CO₂e. This variation over time and in approaches impedes policy-relevant comparisons of monetary values. However, mitigation costs and carbon taxes are often expressed in terms of USD/tCO₂e, making this a suitable metric for values of co-benefits as well (Remais et al., 2014). As shown, this has been used for air quality, but much less frequently for other categories. Conducting monetary valuations in more categories and presenting results in comparable terms – tentatively as USD/tCO₂e – would benefit decision-making. Full comparisons across e.g. political and geographical contexts are probably not possible though, due to large situational variation (e.g. the value of a climate policy that promotes cycling will depend on what type of transportation the cycling substitutes), and in some cases, extending the analysis to monetary valuation may not be worthwhile or appropriate.

Moreover, since a large proportion of the quantitative articles are model-based, i.e. require various assumptions and estimations that are often uncertain, and due to variations preventing comparisons, there is a need for empirical confirmation of model-based results and for other empirical studies, in particular for co-benefit categories where studies so far are comparatively few.

In summary, if co-benefits from all categories, not necessarily limited to the categories reviewed in this article, were quantified and monetized (preferably expressed in USD/tCO₂e), the cost of a climate policy measure could be compared to the full spectrum of its benefits. For air quality co-benefits, empirical validations would be a beneficial complement to model-based results.

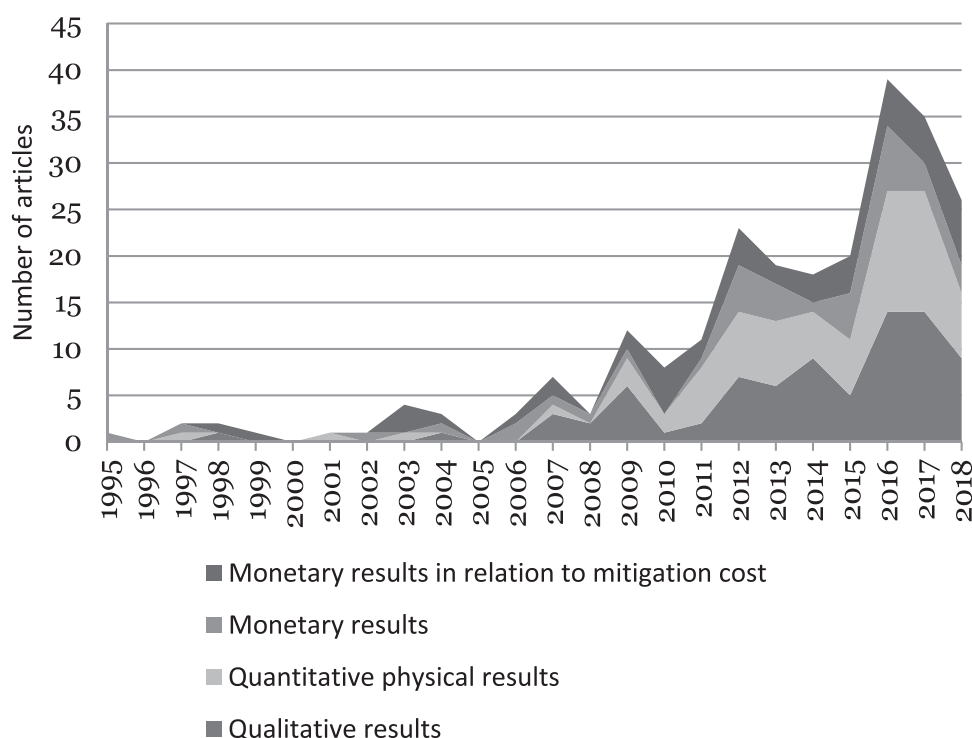


Figure 5. Variation over time in expression of co-benefits.

4.3. Research gaps

It is clear from the review that air quality co-benefits is the most researched category by far. Research gaps are explicitly identified in about a third of the reviewed articles. A number of these underline the need to further explore the co-benefits of mitigation policies and technologies (Biederman & Harpole, 2013; Luo et al., 2017; Macmillan et al., 2014; Wathore et al., 2017; Wheeler et al., 2016), or call for more natural science research of general interest, including on co-benefits (Åström et al., 2013; Zheng et al., 2016). Further exploring specific co-benefits is also commonly called for, e.g. concerning cook-stoves (Anenberg et al., 2012), electricity supply (Gibon, Arvesen et al., 2017), waste and transport (Rashidi, Stadelmann, & Patt, 2017), diet and meat consumption (Haines, 2017; Yip et al., 2013), cycling (Mrkajic, Vukelic, & Mihajlov, 2015) and methane (West et al., 2012). A number of scholars ask for more studies that quantify co-benefits or externalities (Anenberg et al., 2013; Haines, 2017; Longo, Hoyos, & Markandya, 2012; Roberts, 2009; Smith et al., 2016; Yedla & Park, 2009), in particular when based on empirical data (Shaw et al., 2018; Siegmeier et al., 2018; Springmann et al., 2016; Yamazaki, 2017).

An additional number of studies elaborate in detail on research needs linked to co-benefits and their role for policy and integrated decision-making. Krook Riekkola et al. (2011) underline the importance of further studies on co-benefits from a policy transition perspective. Mayrhofer and Gupta (2016b) consider the politics of co-benefits to be inadequately explored and call for scholars from political science and sociology to more critically examine the 'business-as-usual incremental approach' of the concept, whereas Workman, Blashki, Bowen, Karoly, and Wiseman (2018) see a need for research on barriers that prevent co-benefits from being considered in policy-making. In an assessment of knowledge gaps, Gao, Hou et al. (2018) identify the lack of systems for evaluating co-benefits. Similarly, Von Stechow et al. (2016) call for indicators that help to evaluate integrated policies that address multiple sustainable development goals while highlighting co-benefits. More specifically, Wolking et al. (2018) call for researching combined health effects from both diet and mobility behavioural changes. Teng and Jotzo (2014) also see a need for integrating broader effects into economic models typically used in policy analysis (see also Rashidi et al., 2017).

In summary, the reviewed articles point out research needs regarding co-benefits in several specific cases as well as on a general level. We consider it important to generate more knowledge and data about quantitative and monetary values of co-benefits, not least in the areas of diet and active travel due to high policy relevance, as well as knowledge on why and how co-benefits are used, or not used in policy contexts. It is evident that far from all categories in [Figure 1](#) have been sufficiently explored.

4.4. Policy aspects

Several of the reviewed articles stress that both the topic of, and evidence on, co-benefits are commonly overlooked in policy-making (Nemet et al., 2010; Workman, Blashki, Karoly, & Wiseman, 2016). About one fourth of the reviewed articles discuss possible reasons for why this may be the case. Lack of policy integration (i.e. taking several goals into consideration simultaneously when designing policy) stands out among explanations (Alam, Hyde, Duffy, & McNabola, 2018; Antwi-Agyei, Dougill, Agyekum, & Stringer, 2018; Apsimon et al., 2009; Aunan et al., 2004; Cifuentes et al., 2001; Jiang et al., 2013; Kok, Metz, Verhagen, & van Rooijen, 2008; Mendez, 2015; Thambiran & Diab, 2011a; Williams, 2012). A mentioned reason for this is fragmented institutional regimes with multitudes of isolated ministries that deal with particular problems (Antwi-Agyei et al., 2018; Keohane & Victor, 2011). Lack of communication between academic disciplines (Smith, 2014) and knowledge networks (Rennkamp & Boule, 2018) are other mentioned challenges.

The application of inadequate, outdated or geographically differing concepts, methods, approaches or paradigms (Andersen, 2017; Balbus et al., 2014; Workman et al., 2018), as well as lack of knowledge, quantification and monetization (Creutzig & He, 2009; Mendez, 2015; Rashidi et al., 2017; Rennkamp & Boule, 2018; Ščasný et al., 2015) are also referred to as reasons for non-uptake of co-benefits in policy.

An often proposed political solution is to strengthen policy integration. Spencer et al. (2017), for example, argue for a co-benefits approach that includes providing incentives across multiple scales and time frames, promoting long-term integrated impact assessment, and fostering multidimensional communication networks. Several studies point out that visualization and consideration of co-benefits could be helpful when striving for further measures in areas as disparate as e.g. building renovations (Ferreira, Almeida, & Rodrigues, 2017), carbon pricing in Peru (Jakob, 2018), and international climate negotiations (Pittel & Rübbecke, 2008; Takashima, 2017). Applying frameworks that simultaneously focus on internal and external policy coherence as well as horizontal and vertical climate policy integration (Di Gregorio et al., 2017), or that apply multi-criteria decision analysis (Khosla, Dukkupati, Dubash, Sreenivas, & Cohen, 2015), may enable policies to better take co-benefits into account. Here, Bustamante et al. (2014) find that challenges and opportunities for e.g. the land use sector are site-specific, and that deep analysis is needed of how land-use decisions are made and how social, political and economic forces in the future will influence these. According to Remais et al. (2014), health co-benefit models should moreover be developed in concert with policy-making, to be as relevant as possible.

To summarize, it is difficult to see concrete examples among the studies we have reviewed of knowledge on climate policy co-benefits being applied in policy-making. It is also difficult to see any major tendency to implement the various improvement proposals presented in the reviewed articles, for example on integration. The room for improvement is large indeed.

5. Conclusion

This review shows that climate policy co-benefits in general are substantial. While the scientific literature has long been dominated by air quality studies, a broad range of other co-benefits is now being identified and studied, including in the categories of diet, energy security and economic performance. Monetary valuations are less common, but when calculated, co-benefits are often shown to be of the same order of magnitude as estimated mitigation costs, sometimes even larger, despite assessments often being restricted to a few among several co-benefits categories occurring in parallel.

Policy approaches that consider co-benefits have an additional number of advantages. Identifying co-benefits provides policy-makers with a more comprehensive picture of what is at stake, and adds a near-

term positive policy framing since co-benefits are relatively close in time and space. This in turn improves the opportunities for science-based decisions and socio-economically better policies, which can help counteract the ‘wicked’ nature of the climate change problem.

Despite these different advantages, co-benefits are commonly not considered in policy-making. One reason may be that decision-making still often takes place in silos, where single ministries or committees focus on their core issues and often overlook other important dimensions, including co-benefits in other areas. This is pointed out in a number of studies without much visible improvement in terms of, for example, policy integration.

To improve the situation, we propose a number of steps. First, more knowledge on co-benefits is needed, in particular illustrative and comparable quantitative and monetized data. This would benefit from commonly agreed methods for categorizing, measuring and presenting co-benefits, in turn demanding more conceptual harmonization, including broader agreement on definitions. In our view, it is important to then distinguish between Type 1, 2, and 3 co-benefits. More research is also needed on how best to integrate co-benefit data into policy-making, including on how to describe the total value of different categories of co-benefits that in parallel may follow climate policy measures. On these points, organizations such as the IPCC and OECD could potentially provide further typology and guidelines.

Secondly, while being aware of some potential drawbacks associated with the co-benefit concept, political decision-makers ought to make more use of those co-benefits that are already well-known, in order to advance climate policy with rigorous design and simultaneously promote other welfare gains within reach. This would be helped by developing the processes, documentation requirements and criteria for decision-making. Processes in, for example, public climate policy committees should ensure that expertise on co-benefits is brought on board and that adequate studies on co-benefits are conducted. Documentation requirements should similarly ensure that decision-tools, for instance environmental impact assessments and CBA, are always applied so that co-benefits are considered. If co-benefits are not quantified and monetized, tools other than CBA should ideally be preferred for decision-making.

In taking these measures, the scientific and political communities can mutually help to improve policy and mitigate climate change, while fostering welfare for present and future generations.

Notes

1. Pittel and Rübelke (2008) is an earlier brief review. Some recent reviews have a narrow scope, e.g. Ferreira et al. (2017).
2. The IPCC refers to a range of co-benefits in its various reports but often scattered, seldom with monetized data and without giving the topic prominent attention (e.g. IPCC, 2018). This article focuses on journal articles; a detailed evaluation of how IPCC has regarded co-benefits over time would require additional studies.
3. ‘Policy’ refers to public policy, here delimited to climate change mitigation, where cost-arguments against policies are common. Studies solely concerning adaptation are excluded.
4. Up to 1/5/2019.
5. Even earlier is Ayres and Walter (1991).
6. Here ‘green buildings’ are defined as those certified according to the LEED standard.
7. The EU 2020 package has since been complemented with a 2030 Climate and Energy Framework, specifying more stringent targets, as well as with an overriding goal for a ‘climate-neutral’ EU by 2050, see https://ec.europa.eu/clima/policies/eu-climate-action_en (accessed 2 January 2020).
8. REDD - Reducing Emissions from Deforestation and Forest Degradation - is a UN programme mainly focusing on so-called developing countries.
9. Centrally Planned Asia (CPA, including China); South Asia (SAS, including India); Other Pacific Asia (PAS, e.g. Indonesia, South Korea).
10. Double dividend: taxation of carbon-emitters gives climate benefits and reduces distortions when revenues are used to reduce other taxes.
11. See further in Alford and Head (2017) on ‘wicked problems’.

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