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Carbon footprint reduction of the operating room: tools to mitigate the environmental impact of surgical practice

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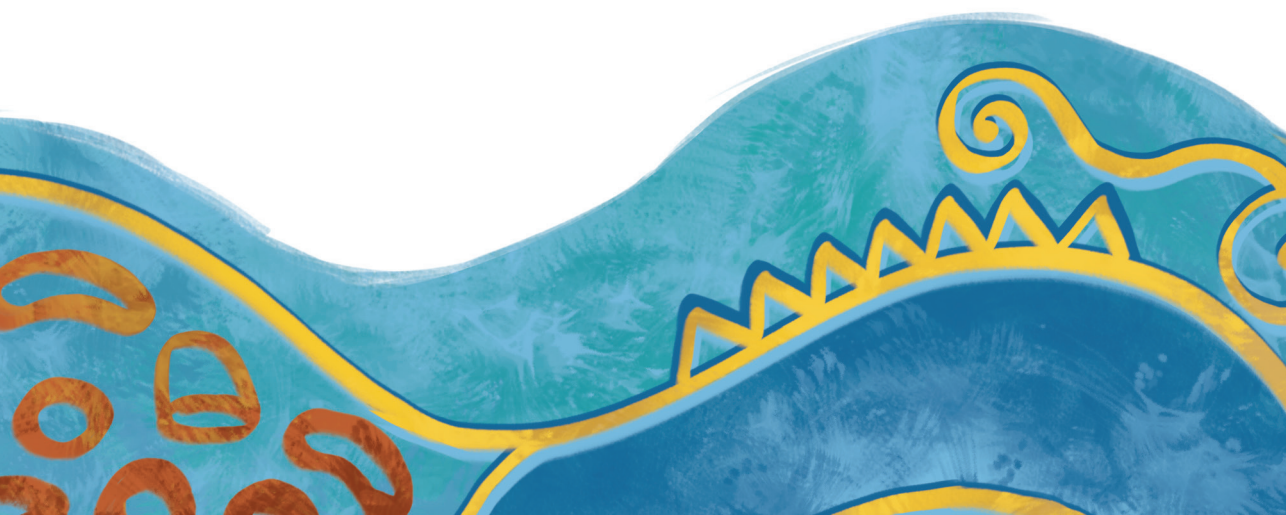
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CHAPTER 7

Surgical Carbon Footprint Auditing Tool for Less Emissions (SCALE): An Evidence-Based Nationwide Cross- Sectional Assessment to Reduce the Environmental Impact of the Operating Room

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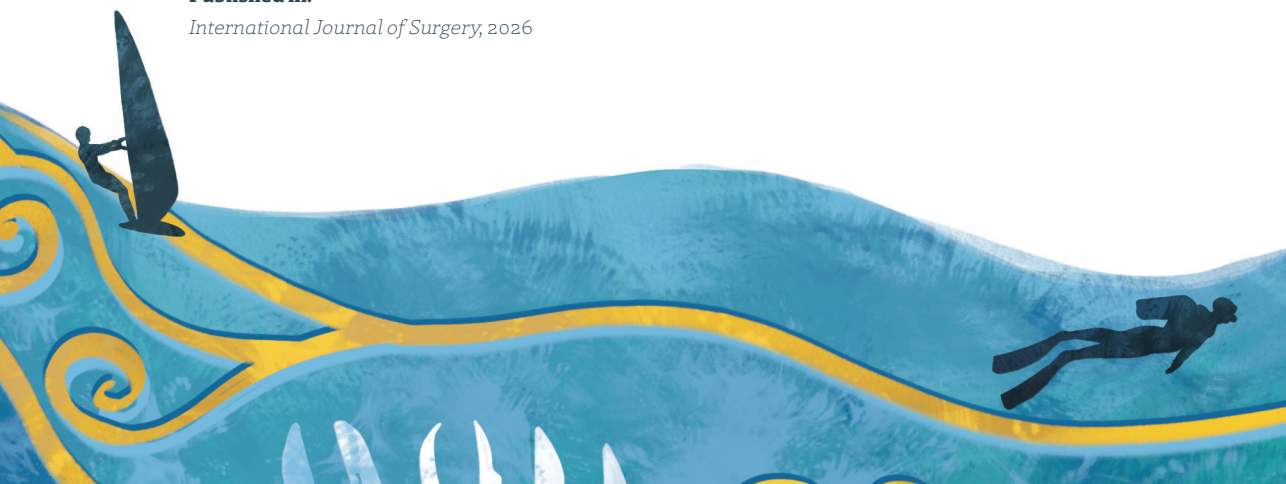
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Abstract

Background: The healthcare sector significantly contributes to global carbon emissions, and operating rooms (ORs) are particularly resource-intensive environments. ORs are therefore potentially impactful targets for emission reduction. Growing knowledge of carbon footprint hotspots in surgery should be integrated into a systematic approach to mitigate the environmental impact of ORs.

Materials and methods: We developed the *Surgical Carbon footprint Auditing tool for Less Emissions* (SCALE), an evidence-based model combining published life cycle assessments (LCAs) with real-world surgical practice to quantify OR-related carbon emissions and high-impact mitigation strategies. A questionnaire assessing qualitative and quantitative aspects of surgical practice was distributed to 60 Dutch hospitals. Collected data were incorporated into the model to calculate the carbon footprint and mitigation potential of individual ORs. Ten priority interventions were provided to each surgical centre. All data were combined to establish a national baseline.

Results: Forty surgical centres (594 ORs) completed the questionnaires. The model consisted of defined variables on surgical practice in five categories, including less-emitting alternatives for carbon footprint calculations: (1) organisation and reporting, (2) energy, (3) anaesthetics, (4) medical products, and (5) decontamination. Implementation of sustainable practices could reduce emissions by 76.3%, saving a mean 729.9 kg CO₂-eq/week per OR. The six most impactful interventions, accounting for over 95% of the achievable reduction, were the transition to renewable energy, phase-out of nitrous oxide and desflurane, use of vapour capture technology and end-tidal control, adoption of heat recovery technology, and use of reusable sterile gowns.

Conclusion: SCALE provides a framework to reduce the carbon footprint of surgical practice by identifying effective measures at the hospital and national levels in the Netherlands. By prioritising these high-impact strategies, SCALE facilitates progress towards sustainable healthcare. Given the urgency of the climate crisis, yielding a rapid and substantial environmental gain with these interventions is crucial.

Introduction

Human health is threatened by the unfolding climate crisis. Rising temperatures and environmental pollution contribute to morbidity, and mortality through multiple direct and indirect pathways, ranging from cardiovascular disease caused by poor air quality, undernutrition as a result of decreased food supply, and vector-related disease due to changes in ecosystems.¹ The healthcare sector is responsible for 4.4% of the global carbon footprint and faces a paradoxical role as both an affected party and contributor.^{2,3}

Hospitals are responsible for substantial proportions of the healthcare-related carbon footprint.⁴ The operating room (OR) is the most resource-intensive environment within hospitals and, therefore, a potentially high-impact target to reduce greenhouse gas (GHG) emissions, which depend on multiple aspects. Energy consumption per m² in ORs is three to six times higher than the hospital average.⁵ In addition, as potent GHGs, anaesthetic gases emitted an estimated 200 kilotonne of CO₂-eq annually in England, 325 kilotonne in Australia, and 12.2 kilotonne in the Netherlands.⁶⁻⁸ Furthermore, single-use items account for 69-87% of the surgical carbon footprint^{9,10} and disposal of contaminated waste contributes substantially to the environmental impact of healthcare institutions.⁹⁻¹¹ Previous research has determined environmental hotspots of ORs and specific types of surgical procedures.^{5,6,10,12-17} Energy and resource consumption vary substantially across sub-specialties depending on procedural duration and medical products.¹⁸ This heterogeneity highlights the necessity for a framework translating environmental hotspots into sustainable measures at individual OR level, while reflecting diverse surgical settings.

This study aims to provide an evidence-based tool to identify and prioritise interventions to reduce the OR's carbon footprint and quantify their potential impact. By integrating literature on environmental impacts of OR-related processes and products, we developed the Surgical Carbon footprint Auditing tool for Less Emissions (SCALE). SCALE enables benchmarking of individual ORs, quantifies carbon footprint reduction potential, and identifies practical interventions to achieve this reduction. By providing a baseline assessment and framework, SCALE facilitates informed decision-making toward sustainable surgical practice at individual and national levels.

STROCCS

This cross-sectional study has been reported in line with the STROCCS guidelines.¹⁹



Methods

Search strategy

The primary outcome of this study was the carbon footprint reduction potential of an individual OR (kg CO₂-eq/week); the secondary outcomes were the interventions to achieve this reduction. To identify the carbon footprint of every OR-related process and product, a systematic literature search was performed in PubMed. Inclusion criteria consisted of English and Dutch articles determining the carbon footprint of products and processes with lower-emission alternatives in surgical practice, without time restriction. Studies on items without alternatives (e.g. medication) were excluded. MeSH terms and free-text words such as 'Carbon Footprint,' 'Operating Rooms,' 'Surgical Procedures,' 'Anaesthetics,' 'Climate Change,' 'Greenhouse Effect,' and 'Medical Waste' were combined with terms related to life cycle assessment (LCA), such as 'life cycle assessment' and 'lifecycle inventory'.

Selection process

In December 2022, two authors (JD, ML) independently screened eligible articles and extracted information on the carbon footprint of energy consumption, anaesthetic agents, single-use and reusable products, and decontamination services. Where multiple LCAs were available for similar processes and products, the study most representative for the Dutch healthcare context was selected. The inclusion and selection criteria are described in Appendix A, Inclusion criteria literature search. As LCAs differ in scope, such as functional unit, and system boundaries, individual results are not directly comparable. However, heterogeneity was accepted as the tool aimed to prioritise high-impact interventions, for which the order of magnitude was more relevant than precise emission values.

Categorisation model

Based on the selected literature, surgical practice was categorised into five domains: (1) organisation and reporting, (2) energy, (3) anaesthetics and medication, (4) medical products and waste, (5) decontamination (cleaning, disinfection and sterilisation). The first category consisted of qualitative indicators of organisational practices that facilitate or hinder transition. It was used to qualitatively assess boundary conditions necessary for implementation.

Standard OR definition

A focus group of clinicians (surgeons, anaesthesiologists, and gynaecologists) with experience in surgical clinics, academic, top-clinical, and regional hospitals in various regions, biomedical engineers, and an OR manager – all with expertise on environmental impacts within their field – defined a 'standard OR'. Consensus was hierarchically

reached, either supported by literature or through group discussion in cases where empirical data lacked (Table 1). Some variables were common surgical practice (e.g. work days per week). The standard OR integrated variables on energy consumption, type of anaesthesia, number of medical products in the OR, and decontamination services.

Carbon footprint calculations

Building upon the standard OR, carbon footprints were calculated using LCA-derived data for every item and process. An example calculation is provided below:

$$\begin{aligned} & \text{Weekly kg CO}_2\text{-eq emitted by surgical gowns per OR} \\ &= \text{GWP sterile surgical gown (disposable or reusable)} \\ & \quad * 3.5 \text{ gowns per surgery} * 5 \text{ surgeries per day} * 5 \text{ days per week} \end{aligned}$$

Carbon emissions factors of fossil fuels and renewable energy were obtained from independent research firms (Gupta Strategists, CE Delft).

Sustainable OR benchmark

To determine the carbon footprint reduction potential of an individual OR, the most 'sustainable OR' scenario (SOR) was used as a benchmark. The SOR represented the lowest achievable carbon footprint for every item and process, according to the obtained literature. Individual OR results were compared with the SOR to identify ten priority interventions to achieve the OR-level reduction potential. From December 2023 onward, each participating surgical centre received an individualised advisory report outlining its performance and recommending what measures to implement.

Data collection

In this cross-sectional study, pilot questionnaires on hospital specific practices across the five themes mentioned above were initially distributed among sustainability officers. Additionally, they were asked to provide data, such as energy contracts, to enhance objectivity. Sustainability officers reported that delivering objective data sources, such as procurement records, required excessive time and effort, and that data gathering was challenging from their position. They suggested that OR managers would have better access to the necessary data across different departments (e.g. procurement). Subsequently, final versions (Appendix A, Table 1) were distributed among OR managers and personnel from 60 Dutch hospitals and five private clinics in June 2023. The OR managers were not asked to provide further objective data but were given instructions on how to collect all required data. By August 2023, 31 hospitals and two clinics had completed the forms. Reminders were sent to the remaining centres. Seven centres replied that they were still occupied, of which three finalised



the forms by December 2023. Four hospitals reinitiated contact and completed questionnaires in 2024. In the case of missing data, hospitals were contacted with a request of completion. Responses up to December 2024 were included in the analysis.

Table 1. *Defined variables included in SCALE.*

	Unit	Boundaries standard OR	Practice in sustainable OR	Source
Nr. of surgeries	/day	5	-	CSP
Hrs. of surgery (energy consumption)	/day	6	100% renewable energy 100% ORs with heat recovery 100% ORs with active night strategy	EC
Nr. of workdays per week	/wk	5	-	CSP
Active weeks per year	/yr	52	-	CSP
Anaesthesia with inhalational anaesthetic agents (MAC hours)	hrs/wk	15	Sevoflurane (carrier gas air) No nitrous oxide VCT End-tidal control	EC
Anaesthesia with TIVA	hrs/wk	15	-	EC
Nr. of sterile surgical instrument trays	/surgery	2	Reusable trays	EC
Nr. of sterile surgical gowns	/surgery	3.5	Reusable gowns	EC
Nr. of m ² surgical drapes	/surgery	4	Reusable drapes	EC
Nr. of laryngoscope handles	/surgery	0.5	Reusable handles	EC
Nr. of laryngoscope blades	/surgery	0.5	Reusable blades	CSP + FGC
Nr. of laryngeal masks	/surgery	0.5	Reusable masks	CSP + FGC
Nr. of blood pressure cuffs	/surgery	1	Reusable cuffs	CSP
Nr. of laparoscopic trocars	/surgery	0.2	Reusable trocars	Literature ²⁰ + FGC
Nr. of laparoscopic scissors	/surgery	0.05	Reusable scissors	Literature ²⁰ + FGC
Nr. of laparoscopic clippers	/surgery	0.05	Reusable clippers	Literature ²⁰ + FGC
Nr. of needle containers	/surgery	0.04	Reusable containers	EC
Nr. of anaesthesia drugtrays	/surgery	1	Reusable trays	CSP

The standard operating variables in average surgical practice, modelled by the focus group, are indicated as boundaries of a standard OR. The most sustainable choice per variable deducted from the included articles in the literature search and the source of the defined variables are also provided. OR, operating room; SOR, sustainable operating room; VCT, vapour capture technology; MAC, minimal alveolar concentration; total intravenous anaesthesia, TIVA; common surgical practice, CSP; expert consensus, EC; focus group consensus, FGC.

Sensitivity analysis

A Monte Carlo simulation with 5,000 iterations was performed to assess the impact of uncertainty in key parameters (Table 1) on the total OR carbon footprint. The surgical hours per day were varied from 4 to 8 ($\pm 50\%$). Similarly, the amount of surgical gowns and sterile trays were ranged $\pm 71\%$ and 50% , respectively, to prevent the average amount needed per surgery from being lower than one. The number of days per week and weeks per year were excluded. All other variables were modelled within clinical ranges ($\pm 80\%$), taking into account different hospital sizes and surgical subspecialties. All parameters were uniformly ranged. The Pearson correlation coefficient of every parameter to the carbon footprint was determined.

All calculations for the tool and Monte Carlo simulations were performed in Microsoft Excel. Statistical analyses were conducted using SPSS Statistics version 29.0.

Results

Literature inclusion

Twelve studies quantifying the carbon footprint of OR-related processes and products were included. These studies assessed (1) the electricity consumption of mixing ventilation and laminar flow, heat recovery, and active night mode; (2) propofol and inhalational gases (desflurane, sevoflurane, and nitrous oxide) and the impact of vapour capture technology (VCT) or end-tidal control (Et Control); (3) both single-use and reusable products such as sterile drapes, laryngeal masks, sharps containers, anaesthetic drug trays, laparoscopic trocars, scissors, and clippers, blood pressure cuffs, laryngoscope blades and handles, surgical gowns; and (4) decontamination packaging.²⁰⁻³¹ Products or services not routinely used across surgical practice, such as bronchoscopes, were excluded. One Dutch study by Bijleveld and Uijttewaai (2022) was identified through the snowballing method.²⁴ An overview of all included items and system boundaries of the standard OR and SOR is provided (Table 1). Incorporating studies with lower-emission alternatives only meant that the model encompassed a defined subset of the OR carbon footprint rather than total emissions. Absolute values should, therefore, not be interpreted as a complete inventory. Detailed information on the included studies is provided (Appendix A, Table 2).

Participating hospitals

Questionnaires were completed by 38 hospitals (63.3%) and two private clinics. The participating surgical centres in our study included 7 out of the 8 Dutch academic hospitals (87.5%), 18 out of 27 top-clinical hospitals (66.7%), and 13 out of 38 (34.2%) regional hospitals. A total of 594 ORs were represented: 172 (29.0%) in academic



hospitals, 310 (52.2%) in top-clinical (high-level non-academic) hospitals, 110 (18.5%) in regional hospitals, and 2 (0.3%) in private clinics. Public data on the total number of ORs in the Netherlands is not available. Figure 1 presents the rate of participating hospitals per province, in which 11 of the 12 Dutch provinces represented. A detailed overview of hospital types can be found in Appendix A, Table 3.

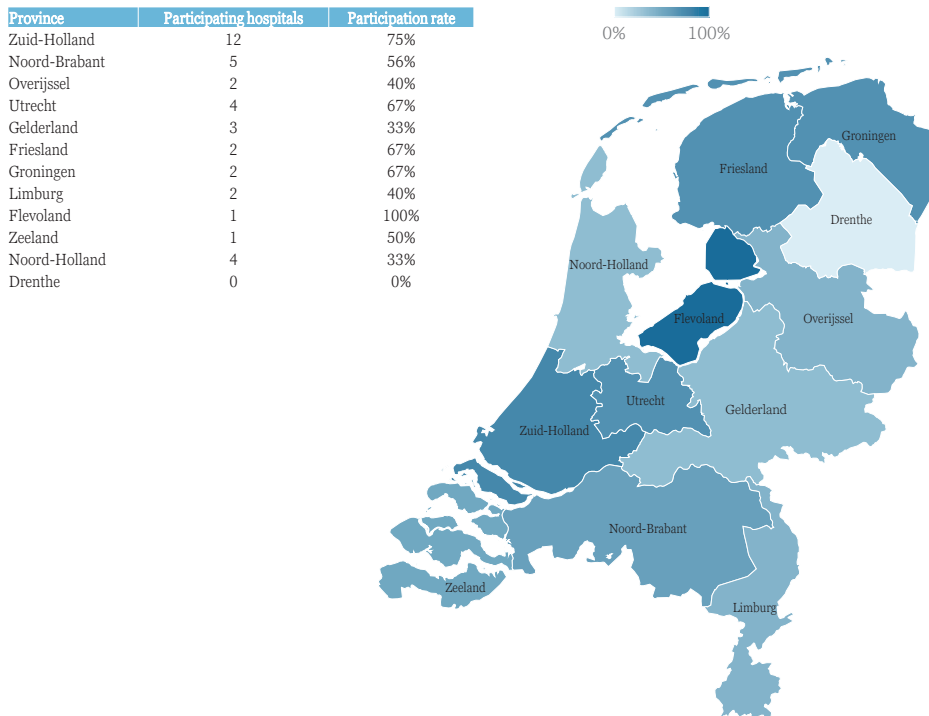


Figure 1. Included hospitals of total per province in the Netherlands.

Evaluated parameters

The category ‘organisation and reporting’ was evaluated in terms of qualitative indicators of organisational practices, such as hospital-level strategy on sustainability instead of carbon footprint. All participating surgical centres reported targets aimed at reducing their environmental footprint. Sustainability was incorporated into staff training in a minority of the hospitals (37.5%), and over one-third (37.5%) of the hospitals did not integrate sustainability in procurement processes. Still, organisational frameworks integrating sustainability in procurement and education did not always align with a lower carbon footprint. The evaluated indicators in this category are provided (Appendix A, Table 4).

In our model, the electricity source (either fossil fuel-based or renewable) was relevant to the carbon footprint of heating, ventilation, and air conditioning (HVAC). In the Netherlands, ORs use three types of HVAC systems: mixing ventilation, laminar airflow, ultra-clean laminar airflow, with increasing hourly air changes and energy consumption, and a decreasing number of particles per m³. In 21 hospitals (52.5%), multiple HVAC systems were available in individual ORs. Energy-limiting measures related to HVAC, including an active night mode – an energy-saving mode – and heat recovery technology, were also assessed.

With respect to anaesthetics, parameters included vapour capture technology (VCT) – a method to recapture inhalational anaesthetics – and Et Control, in which the inhalational anaesthetic dose is precisely regulated. While two-thirds of the ORs had anaesthetic equipment facilitating Et Control, VCT was present in a limited proportion.

Regarding medical products, all evaluated medical products, with the exception of surgical drapes, were reusable in at least one participating OR. At the time of study, laparoscopic trocars and clippers were either hybrid – meaning partly reusable – or single-use. Aiming to prevent unnecessary waste production, products were unpacked exclusively when needed in the majority of the ORs.

Most decontamination services were on hospital premises, and approximately half had water- or energy-saving modes in place. Sterile surgical instrument trays were wrapped in blue wrap rather than reusable containers in most decontamination services. All evaluated categories are presented (Table 2).

Carbon footprint Dutch OR

Within the scope of SCALE, focusing on processes and products with lower-emission alternatives, the average Dutch OR emitted 956.7 kg CO₂-eq/week. The carbon footprint was primarily driven by energy consumption and anaesthetics, contributing a mean (standard deviation) of 377.1 kg CO₂-eq/week (355.4) and 366.2 kg CO₂-eq/week (211.9) respectively. Medical products and waste emitted 196.1 kg CO₂-eq/week (19.3). Decontamination packaging of sterile reusable surgical products contributed 17.3 kg CO₂-eq/week (4.4).

Figure 2 shows the relative impact of individual processes and products to an individual Dutch OR. Fossil fuel-based energy was responsible for the largest share, accounting for 44.8% of the energy used in OR complexes. Desflurane contributed to 7.5% (27.3 kg CO₂-eq/week) of anaesthesia-related emissions and 2.9% of the average per-OR emissions, despite being used in only 15 ORs.



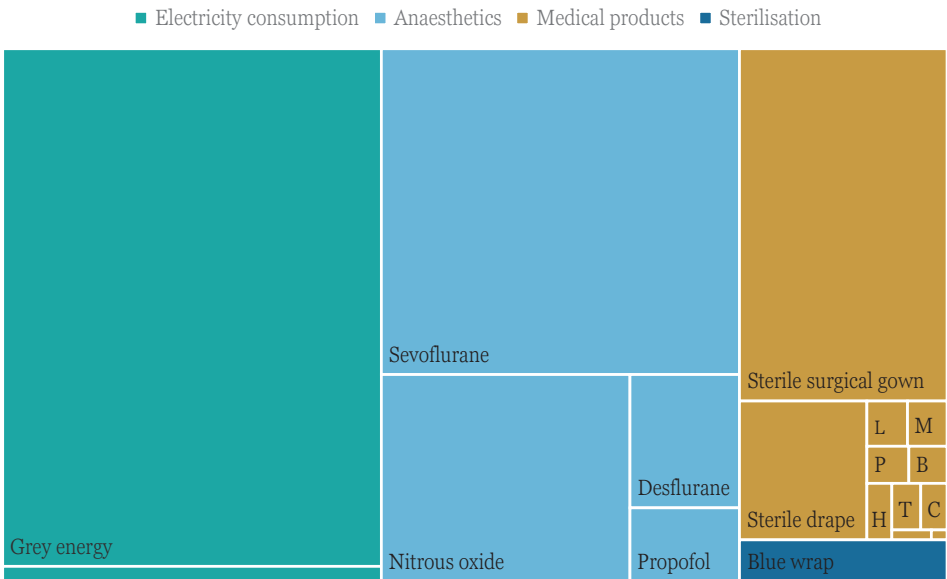


Figure 2. *Per-hospital average emissions per category.* The average carbon footprint related to processes and products in the four categories electricity consumption, anaesthetics, medical products, and decontamination, on a per-hospital level. M= laryngeal mask, L= laparoscopic trocar, B= laryngoscopy blade, T= medication tray, C= laparoscopic clipper, P= blood pressure cuff, H= laryngoscopy handle).

Due to their widespread single-use, sterile drapes and gowns made the greatest contribution to the material-related carbon footprint related. Sterile gowns emitted 140.8 kg CO₂-eq/week per OR and sterile drapes were responsible for 34.0 kg CO₂-eq/week. Laryngoscopy emitted 2.7 kg CO₂-eq/week per handle and blade. Laryngeal masks had a carbon footprint of 3.5 kg CO₂-eq/week. Laparoscopic trocars, scissors, and clippers emitted a total of 6.6 kg CO₂-eq/week, 3.5, 0.8, and 2.4 kg CO₂-eq/week, respectively. Packaging sterile surgical trays with single-use blue wrap caused 18.7 kg CO₂-eq/week, over six times more than sterile surgical instrument trays, which emitted 2.9 kg CO₂-eq/week. Medication trays were responsible for 2.6 kg CO₂-eq/week, and blood pressure cuffs 3.0 kg CO₂-eq/week.

Variation across surgical centres

The five hospitals with the highest and lowest carbon footprints, along with the SOR, are presented in Figure 3. None of the hospitals met the SOR profile fully, indicating a reduction potential across all centres. The two lowest-emitting surgical centres (on a per-OR basis) matched the SOR carbon footprint in the categories energy, anaesthetics, and decontamination. Among the five highest emitting surgical centres, the greatest carbon mitigation could be achieved in the categories energy consumption and

anaesthetics. An OR in the most sustainable hospital in our study had an average weekly carbon footprint of 367.0 kg CO₂-eq, compared to 2,044.9 kg CO₂-eq emitted in the highest-emitting centre. The per-category carbon footprint significantly differed in the anaesthetics, materials, and decontamination categories depending on hospitals sizes, as shown in Table 3.

Reduction potential

On average, transitioning to the SOR led to a yearly carbon footprint decrease of 37,955.3 kg CO₂-eq (76.3%) per OR. Annually, all ORs in our study combined could save 22.5 million kg CO₂-eq. The top ten priority actions in transitioning to a SOR identified by SCALE are presented in Figure 4.

The largest reduction in carbon footprint could be achieved by transitioning from fossil fuel-based to renewable energy, annually saving 18,715.4 kg CO₂-eq per OR. The second most impactful adjustment was the implementation of anaesthetic machines equipped with VCT and Et Control. Eliminating nitrous oxide as a carrier gas could save over 5,000 kg CO₂-eq/year. Switching from single-use to reusable sterile gowns is the fourth most impactful intervention. Adopting these, together with the implementation of heat recovery technology and the phase-out of desflurane would obtain over 95% of the reduction potential of carbon emissions. The carbon footprint related to heat recovery technology is co-independent of the type of energy.

Uncertainty analysis

The uncertainty analysis revealed that the OR carbon footprint had the strongest correlation with the inhalational anaesthesia/TIVA ratio, operating hours per week, and number of surgeries per day. Pearson correlation coefficients for every parameter are provided in Appendix A, Figure 1. Figure 5 presents the carbon footprint distribution of 5,000 iterations. The mean carbon footprint of all simulations was 956.5 kg CO₂-eq/week (95%-confidence interval 949.6 – 963.5 kg CO₂-eq/week) and was nearly identical to the calculated carbon footprint based on the key parameters (956.7 kg CO₂-eq/week).



Table 2. *Evaluated parameters questionnaires.*

	Number of ORs or hospitals
Energy	
Fossil fuel based energy	9 fully, 13 partly (fossil fuel based and renewable)
Renewable energy	18 fully, 13 partly (fossil fuel based and renewable)
Self-generated renewable energy (hospitals)	19 hospitals
Externally purchased renewable energy (hospitals)	30 hospitals
Active night mode	433 ORs
Heat recovery technology	383 ORs
Equipment turned off at night	477 ORs
Mixing ventilation	47 ORs
Laminar flow	202 ORs
Ultra-clean laminar flow	357 ORs
No air handling system	8 ORs
Anaesthesia	
Desflurane	15 ORs
Sevoflurane	<i>Defined variable: 50% anaesthesia hours</i>
Nitrous oxide	311 ORs
Propofol	<i>Defined variable: 50% anaesthesia hours</i>
VCT	42 ORs
Et Control	406 ORs
Low flow	557 ORs
Prefilled syringe	392 ORs
Medication wastage monitoring	84 ORs
Medical products and waste	
Conscious unpacking products	570 ORs
Conscious unpacking integrated in OR protocol	312 ORs
Hazardous and residual waste separation	471 ORs
Paper waste separation	555 ORs
Plastic waste separation	439 ORs
Metal waste separation	296 ORs
Surgical drapes ^a (single-use/reusable/both/none)	594/0/0/0 ORs
Sterile gowns ^a (single-use/reusable/both/none)	553/15/26/0 ORs
Laryngoscope handles ^a (single-use/reusable/both/none)	19/528/47/0 ORs
Laryngoscope blades ^a (single-use/reusable/both/none)	178/233/183/0 ORs
Laryngeal mask ^a (single-use/reusable/both/none)	510/15/69/0 ORs

Total responding ORs or hospitals	Percentage of total responders	Mean related carbon footprint (kg CO ₂ -eq/week) in Dutch OR
40 hospitals	44.8%	366.2
40 hospitals	55.2%	10.9
40 hospitals	47.5%	NA
40 hospitals	75.0%	NA
594 ORs	72.9%	9.8
583 ORs	65.7%	38.7
594 ORs	80.3%	NA
594 ORs	7.9%	Dependent of heat-recovery technology and active night mode
594 ORs	34.0%	Dependent of heat-recovery technology and active night mode
594 ORs	60.1%	NA
594 ORs	1.3%	NA
594 ORs	2.5%	27.3
-		224.6
594 ORs	52.4%	99.2
-		15.2
594 ORs	7.1%	Dependent of inhalational gas used and end-tidal control
594 ORs	68.4%	Dependent of inhalational gas used and VCT
594 ORs	93.8%	NA
594 ORs	66.0%	NA
594 ORs	14.1%	NA
594 ORs	96.0%	NA
594 ORs	52.5%	NA
594 ORs	79.3%	NA
564 ORs	98.4%	NA
568 ORs	77.3%	NA
594 ORs	49.8%	NA
594 ORs	-	34.0
594 ORs	-	140.7
594 ORs	-	2.7
594 ORs	-	2.7
594 ORs	-	3.5



Table 2. *Continued*

	Number of ORs or hospitals
Blood pressure cuffs ^a (single-use/reusable/both/none)	129/396/69/0 ORs
Laparoscopic trocar ^b (single-use/reusable/both/none)	309/18/239/28 ORs
Laparoscopic clipper ^b (single-use/reusable/both/none)	226/53/313/2 ORs
Laparoscopic scissors ^b (single-use/reusable/both/none)	76/171/345/2 ORs
Needle containers ^a (single-use/reusable/both/none)	559/35/0/0 ORs
Medication trays ^a (single-use/reusable/both/none)	99/448/0/47 ORs
Decontamination	
On site CSD	34 hospitals
Blue wrap	542 ORs
Sterile surgical instrument trays	52 ORs
Blue wrap collection	319 ORs
Decontamination equipment turned off	6 hospitals
Decontamination equipment standby	23 hospitals
Energy or water saving modus	20 hospitals

All items included in the final questionnaires, the per OR and hospital answers depending on best suitability. Additionally, the mean related carbon footprint if applicable.) ^aThe single-use/reusable ratio was provided by hospitals.

Total responding ORs or hospitals	Percentage of total responders	Mean related carbon footprint (kg CO ₂ -eq/week) in Dutch OR
594 ORs	-	3.0
594 ORs	-	3.5
594 ORs	-	2.4
594 ORs	-	0.8
594 ORs	-	0.3
594 ORs	-	2.6
40 hospitals	85.0%	NA
594 ORs	91.2%	17.1
594 ORs	8.8%	0.2
594 ORs	53.7%	NA
40 hospitals	15.0%	NA
40 hospitals	57.5%	NA
40 hospitals	50.0%	NA

^bHybrid instruments (partly reusable). CSD, central sterilisation department; VCT vapour capture technology; OR, operating room; NA, not applicable (for example, no quantified related carbon footprint).



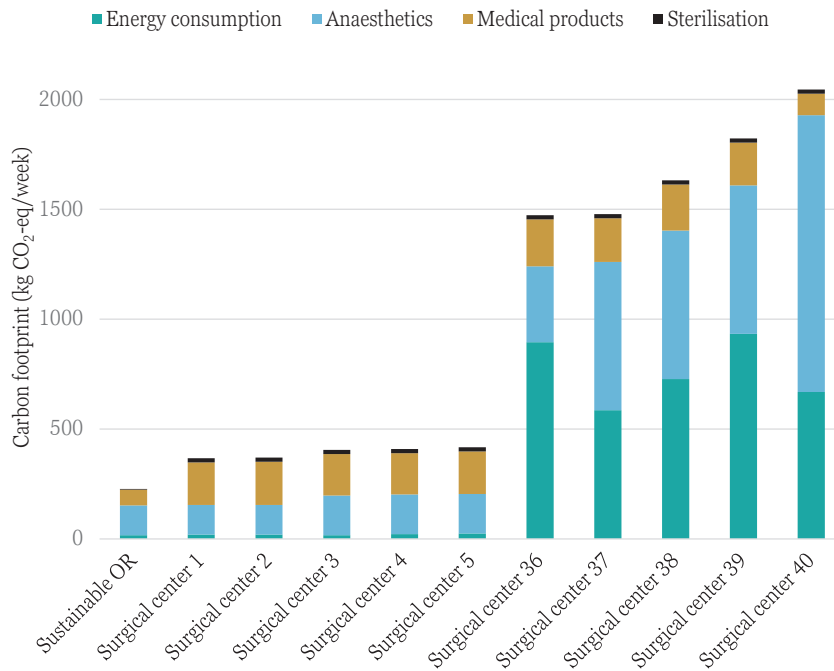


Figure 3. Five surgical centres with the lowest and five the highest carbon footprint compared to the sustainable OR. The total and per-category carbon footprint of the sustainable OR, as well as an OR in the five surgical centres with the lowest and highest-emitting ORs.

Table 3. Average carbon footprint per category in different hospital types.

Carbon footprint OR (Mean kg CO ₂ -eq/ week (range))	Academic hospitals	Top-clinical hospitals	Regional hospitals	Difference in means (p-values)
Energy consumption	382.2 (17.2 – 787.8)	380.9 (17.2 – 933.7)	355.4 (17.2 – 859.7)	0.803
Anaesthetics	365.3 (180.2 – 675.2)	408.6 (135.2 – 1260.2)	248.5 (135.2 – 675.2)	<0.001
Materials	205.5 (190.6 – 229.3)	191.7 (97.6 – 213.7)	194.1 (188.0 – 198.2)	<0.001
Decontamination	16.0 (2.9 – 18.7)	17.6 (2.9 – 18.7)	17.7 (2.9 – 18.7)	0.002

The mean carbon footprint in energy consumption did not differ across hospital types (academic, top-clinical and, regional). The largest relative difference was found in the anaesthetics category.

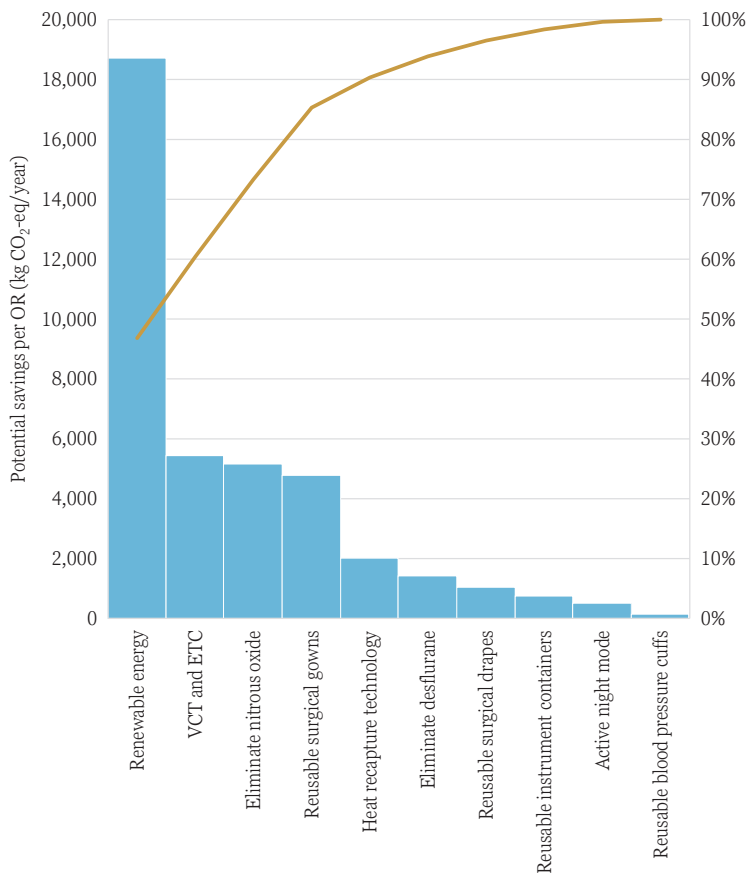


Figure 4. Ten interventions with the largest reduction potential in carbon emissions. Interventions with the largest carbon footprint reduction potential: (1) transition to renewable energy, (2) use vapour capture technology (VCT) and end-tidal control on the anaesthetic machine, (3) eliminate nitrous oxide as a carrier gas, (4) switch to reusable sterile surgical gowns, (5) use heat recovery technology, (6) phase out desflurane, (7) switch to reusable sterile drapes, (8) use reusable sterile instrument trays for decontamination, (9) activate night mode, (10) switch to reusable blood pressure cuffs.



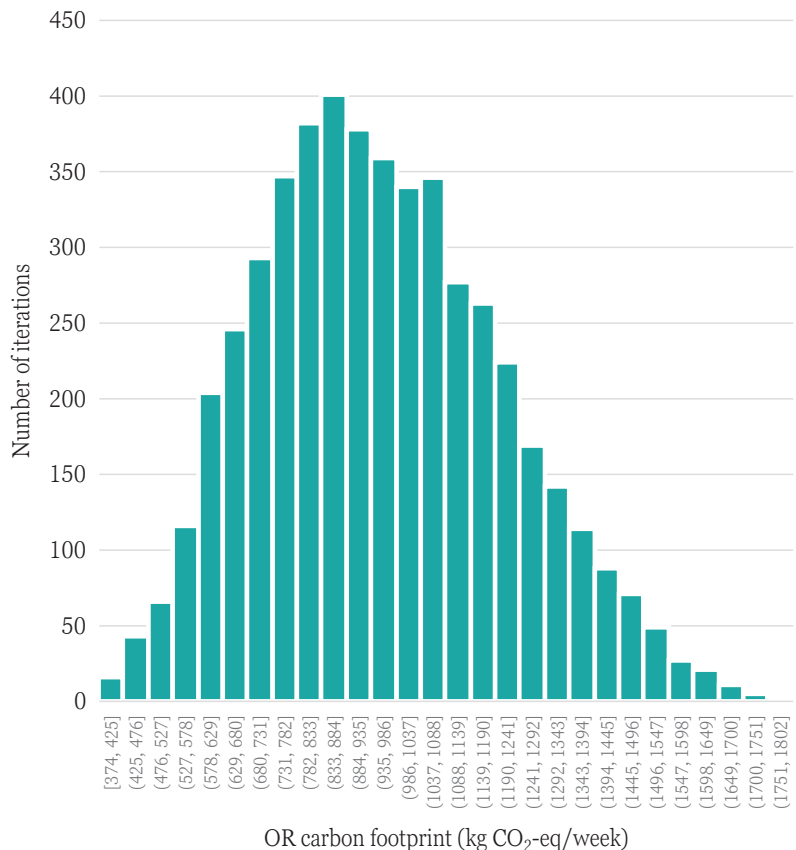


Figure 5. Monte Carlo simulation of variation in base parameters of the SCALE model (standard OR and SOR). The carbon footprint of an individual OR is emitted on a weekly basis when varying the key parameters by a maximum of $\pm 80\%$. The mean carbon footprint in the sensitivity analysis was 956.6 kg CO₂-eq/week (95%-confidence interval 949.6 – 963.5 kg CO₂-eq/week).

Discussion

SCALE provides an evidence-based model to quantify the carbon footprint reduction potential of ORs and identify interventions for sustainable surgical practice. By combining existing LCAs with hospital-specific surgical practice, SCALE eliminates the need for labour-intensive de novo LCAs for individual ORs. To our knowledge, it is the first carbon auditing tool assessing mitigation potential at both individual and national levels.

Main findings

Our findings show that sustainable measures can reduce the carbon footprint by 76.3%, saving 729.9 kg CO₂-eq per OR weekly, equivalent to a one-way flight from Amsterdam to Singapore.³² Six implementations accounted for 95% of the total carbon footprint reduction potential: transition to renewable energy, anaesthetic machines with VCT and Et Control, phase-out of nitrous oxide as a carrier gas, use of heat recovery technology, and reusable sterile surgical gowns. Nearly all SOR parameters were in place in at least one of the ORs, indicating that the SCALE recommendations were both realistic and achievable interventions. Part of the interventions can be sustained by immediate practice change, such as the switch from disposable to reusable products, while other measures, e.g., the procurement of renewable energy, require departmental decisions or might even be policy-dependent. As necessary efforts are expected to differ across hospitals, SCALE enables hospitals to weigh the carbon footprint reduction potential against the expected implementation burden.

Altogether, energy and anaesthetics were carbon footprint hotspots within ORs. Fossil fuel-based energy accounted for 44.8% of the total energy in OR complexes. HVAC systems are known to serve as the main energy consumer in ORs.⁵ In the Netherlands, national protocols indicate HVAC requirements for specific surgical interventions. While Dutch hospitals reported that less than half of the performed surgeries required ultra-clean air, its highly energy-consuming supply system was in place in 94% of the ORs.³³ As we concluded, at least two types of HVAC were available in 21 hospitals, providing surgical teams with a choice. This finding indicates that energy can be saved on an extensive scale by rightly adjusting the classification.

Anaesthetics represented the second hotspot. A study on the carbon footprint of ORs in three academic centres in the UK, Canada, and the USA reported anaesthetics as the largest contributor, with 62% being caused by desflurane and isoflurane.⁵ Despite the rare use of desflurane in Dutch practice (2.5% of the ORs), its phase-out is the fifth most impactful transition to reduce an ORs carbon footprint. This finding aligns with a study reporting that while desflurane and nitrous oxide made up merely 4.1% and 4.6% of purchased inhalational anaesthetics, respectively, their emissions were responsible for 41% and two thirds of the carbon footprint of volatile gases in the Netherlands. The high impact of desflurane and nitrous oxide is explained by their high global warming potential and low potency (nitrous oxide).⁸ The anaesthetic-related emissions were predominantly driven by the use of inhalational anaesthetics. In the sensitivity analysis, the inhalational-to-TIVA ratio had the strongest correlation with the OR's total carbon footprint. Accordingly, shifting to TIVA, when clinically feasible, represents the most impactful anaesthesia-related intervention.



Our results are consistent with a process-based analysis of the carbon footprint of five surgeries, showing that single-use drapes and surgical gowns were among the products with the largest contributions to surgical carbon footprint.⁹ Regarding patient safety, the World Health Organization Surgical Site Infection (SSI) Prevention Guidelines summarize studies comparing the rate of infections in disposable and reusable drapes and gowns across a variety of surgical sub-specialties (e.g. cardiac surgery, orthopaedics). None of the studies, with low to moderate evidence, identified a statistically significant difference in SSI.³⁴ Based on this, the Dutch guideline for infection prevention of SSIs mentions both disposable and reusable surgical drapes and gowns as feasible options.³⁵

We concluded that an integrated hospital-wide sustainable strategy was, in itself, not an indicator of the carbon footprint. This highlights that current improvements were mostly realised through grassroot sustainability initiatives such as 'green teams'. Almukhtar and colleagues found that a lack of knowledge is one of the main challenges for implementation.³⁶ This was confirmed by 42.5% of the hospitals in our study, alongside a lack of time, high costs, and existing contracts with suppliers. Therefore, institutional commitment is required to address complex challenges such as collaboration with procurement and suppliers.

Tools for sustainable practice

Sustainability in healthcare has gained momentum, and various frameworks have been developed. The Greenhouse Gas Protocol provides guidance to practitioners wanting to measure emissions related to medical products and pharmaceuticals.³⁷ It highlights the importance of the LCA approach and serves as the basis for the SCALE design. A practical tool for sustainable surgical practice is the 'Greening the Operating Room Checklist'.³⁸ It identifies opportunities for sustainable practice in the OR in four categories: organisational development, waste, purchasing, and built environment. A similar checklist by the American Society of Anaesthesiologists focuses on both interventions in organisational sustainability meetings and anaesthesiology.³⁹ While these tools highlight mostly intraoperative interventions, the RCSEd Intercollegiate Green Theatre Checklist integrates preoperative, postoperative, intraoperative, and anaesthesia-related recommendations.⁴⁰ These checklists provide extensive suggestions that can serve as useful guides for sustainable surgical practice. However, the impact of the interventions is not quantified. To distinguish high- and low-impact measures supporting decision-making, SCALE calculates the environmental impact of (part of) these interventions and adjusts it to individual levels. Still, SCALE covers only part of the interventions in the abovementioned checklists, as it does not include interventions for which carbon footprint data remain unavailable.

Limitations

Several limitations should be noted. First, the environmental impact is broader than carbon footprint.⁴¹ SCALE reported only on the carbon footprint as a result of the 'Green Deal for Sustainable Healthcare', an agreement for the Dutch healthcare sector distilled from the national climate agreement, aiming to reduce carbon footprint by 55% before 2030.⁴² Dutch healthcare institutions are focusing on carbon emission reduction as a result of this agreement, and SCALE facilitates this goal. Furthermore, the carbon footprint is generally consistently reported upon in environmental studies in healthcare. Limiting the outcome to carbon footprint enhanced the amount of studies included in the tool and provided single-way results. Still, we encourage other scientists to integrate as many environmental impact categories as possible to provide complete conclusions on sustainable practice.

Secondly, integrating LCAs from multiple sources in one tool limits strict comparability and introduces uncertainty in carbon footprint values. The intent of this first-generation tool was to identify high-impact strategies for sustainable surgical practice. Exact carbon footprint figures may be influenced by the differences in LCA scope and methodology, meaning that caution in interpretation is required. The tool does, however, still offer the ability to identify and distinguish high- versus low-impact interventions for carbon footprint reduction. Moreover, the structure of the tool provides the possibility of adaptation to new insights, both operational and environmental impact-wise. The incorporated literature was specifically tailored to the Dutch context for this national benchmark, and further practice-based refining is both necessary and feasible before implementation in another country.

Another limitation is the possible variability in reporting of the questionnaires. While the questionnaires were accompanied by instructions on where to obtain accurate information, the reported data was not complemented by objective sources such as procurement records. Due to the extensive profile of the questionnaires, we attempted to limit their extent to enhance maximal participation.

Lastly, real-time results may deviate from our conclusions as the model was based on a standardised set of variables. These are an inherent simplification of highly variable surgical practice, considering case-mix, hospital size, and complexity of procedures. This standardisation ensured a fair comparison of carbon footprint based on sustainable choices and organisation rather than volume. The uncertainty analysis showed a limited impact of variations in the key parameters on the carbon footprint outcome. Moreover, this standardisation ensured a fair comparison of carbon footprint based on sustainable choices and organisation rather than surgical volume.



Future perspectives

Following this measurement, the Dutch Ministry of Health, Welfare, and Sport received a report providing hotspots and focus points on a national scale, aimed at facilitating sustainable surgical practice from a higher policy level. SCALE has been incorporated in national certification for sustainable practice in healthcare institutions.

Future research should focus on evaluating the adoption of recommended interventions and motives driving their uptake, as well as barriers to implementation, including economic trade-offs. As SCALE is a dynamic model, it will be updated with emerging literature potentially integrating more environmental indicators. A follow-up measurement will be performed approximately two years after baseline – providing a window to implement the advised interventions. Lastly, an international upscale of SCALE represents an opportunity for even greater environmental benefits.

Conclusion

In conclusion, if we want to counteract the paradoxical role of the highly emitting healthcare sector and advocate for better human health, high impact interventions should be pursued in the resource- and energy-intensive OR environment. SCALE identified these measures on both a local and national level. The national framework ‘Sustainability in guidelines: Adding sustainability aspects in guideline development for the OR’ can facilitate their embedding in surgical guidelines.⁴³ Integration of the most effective SCALE measures in these guidelines presents an evidence-based approach and stimulation of clinical action toward enhancing both planetary and human health. Without urgent actions to counteract the surgical carbon footprint, healthcare will continue to have a detrimental effect on the very health it intends to protect.³

Appendix A.

Supplemental digital content.

<https://links.lww.com/JS9/H528>

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