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Identifying and assessing effectiveness of alternative low-effort nitrogen footprint reductions in small research institutions

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Abstract

Concern over the ecological damage of excess nitrogen has brought increased attention to the role of research institutions and universities in contributing to this problem. Institutions often utilize the concept of the ecological 'footprint' to quantify and track nitrogen emissions resulting from their activities and guide plans and commitments to reduce emissions. Often, large-scale changes and commitments to reduce nitrogen footprints are not feasible at small institutions due to monetary and manpower constraints. We partnered with managers in the dining and facilities departments at the Marine Biological Laboratory (MBL), a small research institution in Woods Hole, Massachusetts, to develop five low-effort strategies to address nitrogen emissions at the institution using only resources currently available within those departments. Each proposed strategy achieved emissions reductions in their sector and in the overall nitrogen footprint of the MBL. If all modelled strategies are applied simultaneously, the MBL can achieve a 7.7% decrease in its nitrogen footprint. Managers at MBL considered strategies that required no monetary input most feasible. The intersection of carbon and nitrogen emissions also means the modelled strategies had the co-benefit of reducing the MBL's carbon footprint, strengthening the argument for applying these strategies. This paper may serve as a model for similar institutions looking to reduce the ecological impact of their activities.

1. Introduction

Nitrogen is essential to all living organisms but human activities are increasingly altering the nitrogen cycle at a global scale. Primarily through the use of nitrogen fertilizers for agriculture and emissions from burning fossils fuels, human activities now create 3–4 times more reactive nitrogen globally then do natural terrestrial processes (Fowler *et al* 2013). Once released, excess nitrogen causes a cascade of changes as it moves through the environment with damaging effects on human and ecosystem health. These include acid rain, smog, stratospheric ozone depletion, biodiversity loss and coastal eutrophication (Galloway *et al* 2003, 2008, Erisman *et al* 2008). Excess nitrogen released by human activities also interacts with the global carbon cycle to alter the greenhouse effect (Gruber and Galloway 2008).

Important to mitigating the damaging effects of excess nitrogen is addressing the sources of pollution. Critical to this process is connecting entities, from individuals to entire countries, directly to nitrogen losses to the environment as a result of their resource use. The ecological 'footprint' concept was developed for this purpose and has increasingly been applied to nitrogen as concern over its emission grows (Galloway *et al* 2014). A nitrogen footprint enables an entity to understand their role in the global nitrogen cycle, quantify the scope and scale of its nitrogen emissions, and monitor changes over time (Galloway *et al* 2014, Castner *et al* 2017). As concern over the environmental impact of their activities has increased, universities and other academic and research institutions have begun to leverage the nitrogen footprint to identify activities that contribute to their nitrogen emissions and where actions that reduce those emissions can be applied.

Studies at universities and other institutions of higher education have often taken a top down approach to reducing institutional nitrogen footprints. This approach starts with reduction commitments from the institution's governing body, approving a strategic reduction plan, or in some cases amending existing sustainability commitments to include nitrogen emissions (Leach *et al* 2013, Barnes *et al* 2017, Castner *et al* 2017). This approach may not be immediately feasible for smaller institutions with limited resources. Such institutions require an alternative approach. Studies of US households have found that small changes in individual behaviour can effectively reduce household environmental footprints at levels large enough to impact the overall carbon footprint of the country (Dietz *et al* 2009, Laitner *et al* 2009, Jones and Kammen 2011). Likewise, strategies requiring relatively minor investments of money and manpower may have the capacity to lower institutional nitrogen footprints when applied as part of more comprehensive reduction plans (Barnes *et al* 2017, Castner *et al* 2017, Leary *et al* 2017). These examples provide support for the idea that emissions can be reduced via incremental, low-effort strategies. There does not seem to be, however, a single novel, cheap 'magic bullet' applicable everywhere. Operational needs, stakeholder interests and specific regulations and policies differ across different institutions, making the identification of these low-effort strategies and the assessment of their effectiveness at reducing nitrogen footprints challenging. Contrasts in local conditions and interests demand different combinations of options be evaluated and considered to ensure management of institutional nitrogen footprints is effective and acceptable.

The Marine Biological Laboratory (MBL) is a small, private, research institution located in Woods Hole, Massachusetts, and affiliated with the University of Chicago. The institution is home to approximately 250 year round scientists and staff. Every summer the institution hosts up to 4000 visiting scientists and students through its courses and conference programs. Though the seasonal pattern of visitors is unusual, the MBL is similar to many other small institutions and colleges in that it houses and feeds users in campus facilities where their activities contribute to the institution's nitrogen emissions. The first MBL attempt to calculate its nitrogen footprint took place between 2011 and 2013, as part of student projects. The calculations were formalized and completed for calendar year 2016 (de la Reguera *et al* 2017).

Though the MBL has been calculating and tracking its nitrogen footprint for several years, it currently has no formal nitrogen reduction goal. Like many institutions of its size, acquiring the resources to accomplish major changes in the MBL's operations to reduce nitrogen emissions is challenging. In this landscape of operational limitations and budgetary constraints, alternative low-cost strategies may help provide the proof of concept for N footprint reductions and serve as the starting point for more ambitious measures to be developed and applied in the future.

The primary goal of this study is to explore a bottom up approach aimed at identifying 'low-effort' strategies and assessing their effectiveness at reducing institutional nitrogen footprints. This paper explored small changes department managers at MBL can make to reduce nitrogen emissions with little investment from the institution and modelled the impact these changes have on the MBL's nitrogen footprint. We define these strategies as 'low-effort' meaning they can be employed immediately with current resources while the MBL builds capacity for larger changes that will require more investment. Strategies reducing nitrogen emissions may have co-benefits including reducing carbon emissions and costs. Therefore, in this study we also assessed the impact that selected low-effort strategies may have at reducing the MBL's carbon emissions. Together these strategies serve as a roadmap to a 'bottom up' approach to reducing the environmental impact of an institution's activities.

2. Methods

2.1. Baseline footprint calculations

The Marine Biological Laboratory's footprint for calendar year 2018 was calculated and then used as a baseline footprint. The boundaries for the footprint include fuel emissions from buildings and vehicles at the Woods Hole campus as well as from MBL owned property and vehicles at two field research sites located at Plum Island, Massachusetts and Toolik Lake, Alaska. This includes natural gas for heating buildings and gasoline and diesel fuel for research trucks and boats and summer commuting shuttles. Also included were emissions from purchased electricity at the Woods Hole and Plum Island buildings as well as an offsite warehouse space, and solar energy generated from a small rooftop array. Emissions from year-round staff commuting to and from work, travel to and from MBL by summer course faculty and staff, year round business related travel (air, bus, train, and car), waste and wastewater, grounds fertilizer, refrigerants, and paper products were also included. The MBL has two dining facilities, a traditional dining hall that operates in the summer months serving primarily visiting students and conferences, and a smaller café open year round for lunch. Emissions from the production and consumption of food at these facilities was also included in the baseline footprint. In 2018 the MBL began composting kitchen food scraps in a limited capacity with the help of an outside composting company which is included as footprint offset in the baseline calculations.

Individual stakeholders in MBL's Accounts Payable, Facilities, Education, Human Resources, and Dining departments provided data needed to calculate the emissions of the various sectors. The baseline footprint was calculated using the Sustainability Indicator Management and Analysis Platform (SIMAP, https://unhsimap.org/home). This platform simultaneously calculates nitrogen and carbon emissions based on data entered by the user. The nitrogen footprint is reactive nitrogen, all species of nitrogen except N_2, converted and reported as the total weight of reactive N. The carbon footprint includes the six major greenhouse gases, for CO_2, CH_4, N_2O, hydrofluorocarbons (HFCs), perfluorochemicals (PFCs), and sulfur hexafluoride (SF6) emissions reported as a single sum of CDE (carbon dioxide equivalent). SIMAP uses a set of standard emission factors to determine nitrogen emissions associated with food consumption at MBL as well as the virtual nitrogen factor (VNF): emissions related to the growth, harvesting, and processing of purchased foods, upstream of its consumption at MBL (Galloway *et al* 2007, Burke *et al* 2008, Leach *et al* submitted). Further information regarding SIMAP's emission boundaries, calculation, and conversion methods are described by Leach *et al* (2013), Leach *et al* (2017) and Leach *et al* (submitted).

2.2. Reduction strategies development

At most academic institutions, food production and consumption, stationary fuels, utilities, and wastewater are the largest contributors to the nitrogen footprint (Castner *et al* 2017). Previous footprint calculations indicate that the same is true at MBL (Castner *et al* 2017, de la Reguera *et al* 2017). Therefore, our efforts to identify low-effort reduction strategies focused on actions that target emissions in these sectors. For the purpose of this study a 'low-effort' strategy is defined as an action that: (a) requires minor modifications of operations, (b) requires little monetary investment, (c) requires no additional manpower, (d) is acceptable to users/consumers, (e) is feasible to be implemented in the short term (within the next 3–5 years). Emission reduction strategies were developed with direct input from department managers. We conducted in-person interviews with the institution's dining manager and representatives from the facilities and operations department. In each interview, we presented the baseline footprint calculations and the relative contributions of specific activities and operations, highlighting the importance of emissions from the manager's specific department in the overall footprint. We identified areas or sectors where reductions can be applied. We then discussed strategies for reducing emissions in those sectors, including initiatives already underway, or goals the managers had for their departments.

After reduction strategies were identified, we discussed the feasibility of the different actions. The goal was to take into consideration only those strategies that managers identified as low-effort according to the five criteria defined above. Each proposed strategy was evaluated according to each of these criteria on a scale of high, medium and low feasibility.

After the interviews we conducted literature reviews and follow up interviews with the managers to obtain the data needed to model the various reduction strategies. The footprints under each selected reduction strategy were modelled in SIMAP. Data from the 2018 footprint in the food, compost, waste and wastewater, and utilities sectors were used to make reduction strategy calculations (as described below). Data from all other sectors not related to these scenarios (waste, wastewater, business travel, transport fuels, commuting, etc) were kept constant (2018 baseline values).

2.3. Reduction scenario boundaries and calculations

Interviews with MBL's managers helped identify a number of actions and strategies to reduce nitrogen emissions in the dining and facilities sectors. Among the many options discussed, managers in the MBL's dining and facilities departments selected five individual nitrogen emission reduction strategies they felt were feasible for their departments. Three address emissions in the dining department, two are utilities specific. In addition, a combined strategy, which simultaneously implements all five individual strategies, was modelled. The details of each strategy are described below and summarized in table 1.

3. Dining-related reduction strategies:

Reduction strategies in this area focused on reducing meat, especially beef consumption, and reducing food waste. Decreasing meat is an effective means of reducing nitrogen and carbon losses to the environment (Garnett 2016, Harwatt *et al* 2017, Leach *et al* submitted). MBL's dining services provides employees, conference attendees, and visiting students satisfying meals within strict dietary, financial, and environmental constraints. Based on these constraints, and the feasibility criteria by which all strategies were assessed, we discarded more ambitious options that included, for example, entirely vegetarian menus for conferences, or reducing upstream food waste by purchasing less food overall. Our dining manager felt these options would be too disruptive to diners and her kitchen staff. Ultimately, we modelled three strategies that can be realistically implemented over the next 3–5 years.

3.1. Substituting 20% of beef with poultry and fish (less beef)

Substituting beef for meats with lower VNFs will reduce the nitrogen footprint of food with less disruption to dining operations. This option is also more palatable to diners (table 1). Some beef-based meals,

Table 1. Descriptions of modelled reduction strategies and feasibility assessment across five categories and overall feasibility as perceived by relevant MBL managers.

Strategy	Description	Modification in operations	Monetary impact	Manpower investment	Acceptability to consumers	Time-line	Overall feasibility
Dining related							
Less meat	Substitute 10% meat (−1675 kg) with beans (+1340 kg) and vegetables (+335 kg)	None anticipated—possible using current food supply chains and kitchen facilities	No investment, some savings in food cost	Short term effort to update menus to substitute meat for vegetarian options	Some impact-vegetarian options popular with conference and courses Some year–round staff may be affected	Short	Moderate
Less beef	Substitute 20% beef (−550 kg) with poultry (+385 kg) and fish (+165 kg)	None anticipated—possible using current food supply chains and kitchen facilities	No investment, little to no savings anticipated	Short term effort to update menus to substitute poultry and fish for beef	No impact anticipated-poultry and fish already popular options	Short	High
More composting	All kitchen and dining food waste composted (8980 kg annually)	None—composting already taking place in kitchen	Annual cost of contract with third-party composting company, cost of new compost bins	Short term effort to educate staff and diners about composting Compost added to daily workload of current staff	No impact anticipated—diners and kitchen staff put food scraps in compost rather than trash	Short	High
Facilities related							
Upgrade lighting	Upgrade lighting fixtures, install LED bulbs and occupancy sensors. Save 487 426 kWh annually	None anticipated	Substantial upfront cost offset by annual energy savings	Short term effort to complete upgrades	No impact on building occupants	Medium	High
More solar	Purchase RECs for 2018 PPA Claim 473 000 kWh solar energy annually	None anticipated	Substantial annual cost of purchasing RECs	None anticipate	No impact on MBL staff or guests	Short	Moderate

such as burgers or steaks, served as the final meal for visiting conferences and courses, could be replaced with seafood options such as lobster or swordfish, already popular with diners. In other cases, poultry could replace beef in a dish, for example a turkey chili. Coupling these strategies, the MBL dining manager felt up to 20% of the beef served in the dining halls could be replaced with other animal proteins. This translates purchasing 0.55 metric tons (mt) less beef annually. Seventy per cent of the difference is made up with poultry (0.39 mt) and 30% with fish (0.17 mt). Pork was considered an unacceptable substitute due to the number of diners who avoid it for religious reasons. Fish has the lowest VNF of all animal proteins (Leach *et al* submitted), is already popular amongst MBL diners, and is readily available thanks to the institution's coastal location.

3.2. Substituting 10% of meat with vegetable proteins (less meat)

Though an entirely vegetarian menu would be currently unacceptable to most MBL diners, the MBL dining manager agreed that reducing the amount of meat served would be acceptable to diners and would require little to no changes in operations, monetary investment, or additional manpower (table 1). By serving more vegetarian entrees with meat as a side and initiatives such as 'Meatless Mondays', a program in which no meat is served on 1 d every week (Meatlessmonday.com) the dining manager believes the amount of meat served at MBL can be reduced by up to 10%. The MBL dining locations served 16.8 mt meat in 2018. In this scenario 10%, or 1.68 mt is removed, split equally between the four types of meat served. Based on feedback from the dining manager, in this scenario 80% of difference is made up with beans (1.34 mt) and 20% with other vegetables (0.34 mt).

3.3. Composting all kitchen and table food waste (more composting)

The MBL dining hall began composting kitchen food scraps in 2018 with the help of a third-party contractor who collects food scraps and composts them in an offsite facility. The dining manager considers composting the most feasible way to reduce the environmental impact of her department. Expanding the existing program will not affect consumers and requires no modification of operations or additional manpower (table 1). Through a combination of better signs, more education for diners, and training for staff she estimates all food waste from the kitchen and dining hall can be composted. When adjusted for different needs in the busy summer season and slow winter season, this is a 200% increase from 2018. In this scenario, MBL composts 8.98 mt compost a year. Though composting does not affect the nitrogen footprint of food purchased, it is included as a dining related scenario because it occurs in the dining facilities and will require a slight change in operations in that department (table 1). Composting is included as an offset to both the nitrogen and carbon footprints. The process of composting removes these nutrients from the MBL's system bounds, recycles nitrogen and sequesters carbon preventing their release to the environment. Additionally, increasing composting will reduce the weight of landfilled food waste by 8.98 mt annually.

4. Utilities-related reduction strategies

Emissions from stationary fuels are the third largest source of nitrogen, and largest source of carbon emissions at the MBL. However, interviews with facilities department managers revealed that, the ageing heating system, the lack of centralized control over heating and cooling in campus buildings, and the prohibitively expensive upgrades to the campus heating systems, make it impossible to include actions aimed at reducing stationary fuels as feasible, low-effort strategies. Managers in the facilities department agreed on the feasibility of reducing emissions from electricity consumption at the MBL and helped us define two strategies.

4.1. Upgrading the campus lighting fixtures and control systems (upgrade lighting)

At the time of our calculations, the facilities department was already planning an overhaul of the campus's lighting systems making it a highly feasible strategy despite necessary inputs of money and manpower (table 1). The overhaul includes upgrading fixtures, replacing traditional bulbs with LED, and adding occupancy sensors. Based on an audit performed by an outside energy company, these upgrades will save the institution 487 mWh annually. This translates to a 6.3% overall decrease in campus electricity use.

4.2. Purchasing Renewable Energy Credits for solar energy (more solar)

In 2018, the MBL was engaged in several solar purchased power agreements (PPAs). This includes 473 600 kWh from a third-party solar company. In the current agreement, MBL purchases the electricity but not the associated Renewable Energy Credits (RECs) and therefore cannot claim this power as an offset in its footprints. This strategy models the impact of purchasing the RECs for PPAs on the MBL's nitrogen footprint. This strategy requires no change in operations, no investment of manpower, and will not impact building occupants. However, because it requires an annual purchase, the facilities managers ranked it medium for overall feasibility (table 1).

In addition, we modelled the combined impact of applying all five strategies simultaneously. In this scenario, the 'Less Beef' and 'Less Meat' strategies were combined sequentially by first reducing the amount of beef served by 20% from 2018 levels then reducing the total amount of meat served by 10%.

5. Results

5.1. 2018 baseline footprint

In 2018, the activities, functioning and operations at the MBL generated a footprint of 6.68 metric tons of nitrogen. Food production and consumption were by far the largest sources of nitrogen emissions at MBL, accounting for 72% of the total footprint (figure 1). Utilities (8.3%) and stationary fuels (8.0%), and commuting (6.3%) were also important contributors to the total nitrogen footprint (figure 1).

Within the footprint of food alone, meat (beef, poultry, fish, pork) is the largest source of nitrogen emissions. The MBL purchased 16.8 metric tons of meat in 2018, which disproportionally contributes to emissions as it represents only 7.1% of the total weight of all food purchased but 19.3% of the nitrogen footprint of food. In contrast, plant items (fruit, vegetables, potatoes, grains, beans and pulses) are 75.6% of

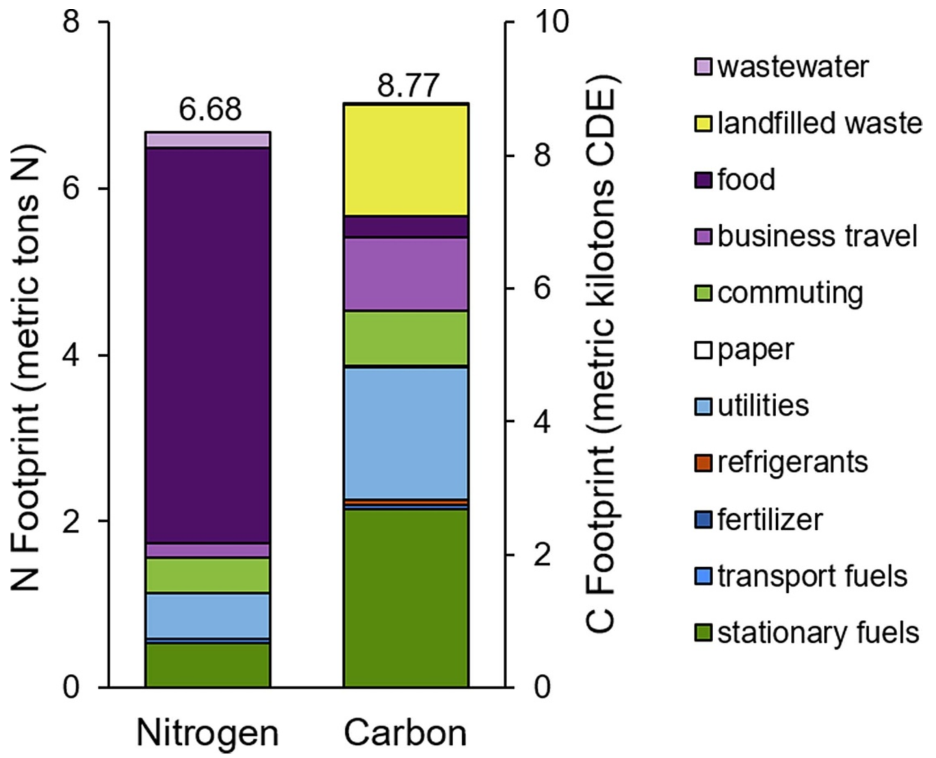

Figure 1. 2018 baseline nitrogen and carbon footprints at the Marine Biological Laboratory broken up by sector. Nitrogen footprint is shown in units of metric tons nitrogen. Carbon footprint is shown in metric kilotons carbon dioxide equivalent. Data labels display total footprint.

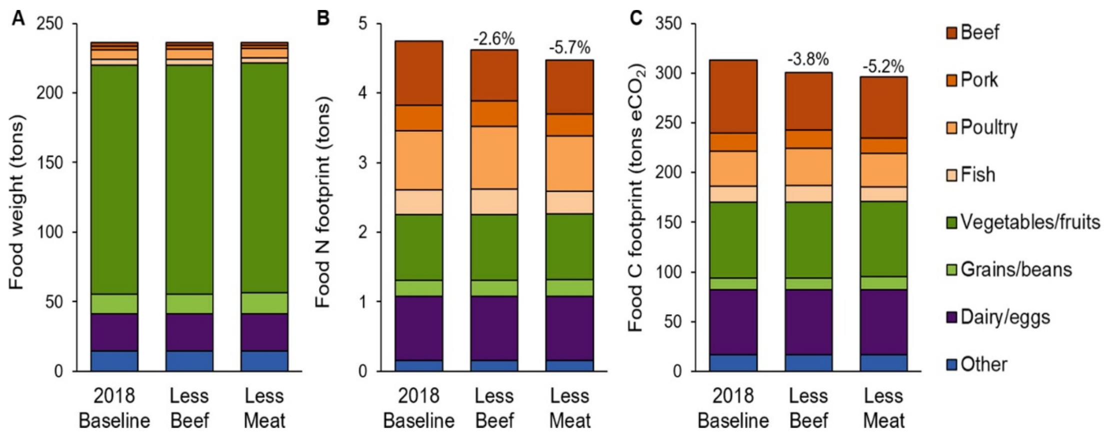

Figure 2. Comparison of the weight (A) nitrogen (B) and carbon (C) footprints of food purchased in baseline year 2018 and under dining related emission reduction strategies broken down by food type. Data labels display per cent reduction from the baseline footprint. The 'More Composting' strategy is not included as composting does not impact the footprint of food purchased.

the total food purchased but only 24.8% of the nitrogen footprint of food respectively (figures 2(A) and (B)). Electricity generation contributes 94.5% of the utilities nitrogen footprint. Transport and delivery losses contribute the remaining 5.5% (figure 3(A)).

In 2018 the MBL's carbon footprint was 8.77 metric kilotons of carbon dioxide equivalent (figure 1). Unlike nitrogen, food did not contribute a large percentage of the carbon footprint. Instead stationary fuels (30%), utilities (24%) and landfilled waste (19%) were the largest sources of carbon emissions while food made up only 3.5% of the total carbon footprint (figure 1). However, similar to nitrogen, within the footprint of food only, meat contributed disproportionately (46%) to the carbon footprint of food (figure 2(A) and (C)). Electricity generation made up 94.9% of the footprint of the utilities sector (figure 3(B)).

5.2. Impact of strategies on nitrogen and carbon footprints

All of the modelled strategies achieved reductions in the nitrogen footprint of their target sectors and were considered at least moderately feasible by the

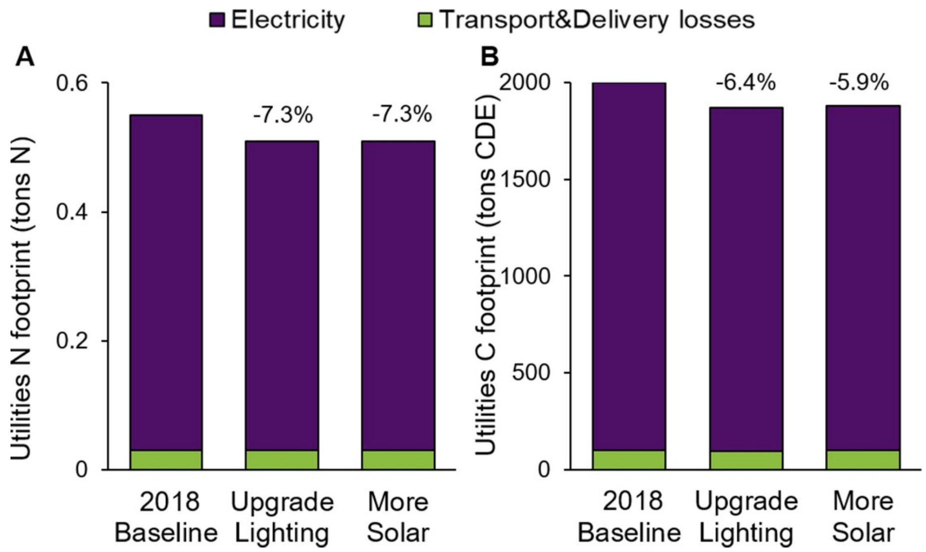

Figure 3. Comparison of nitrogen (A) and carbon (B) footprints of the utilities sector in baseline year 2018 and under two utilities related emission reduction strategies by source. Data labels display per cent reduction from the baseline.

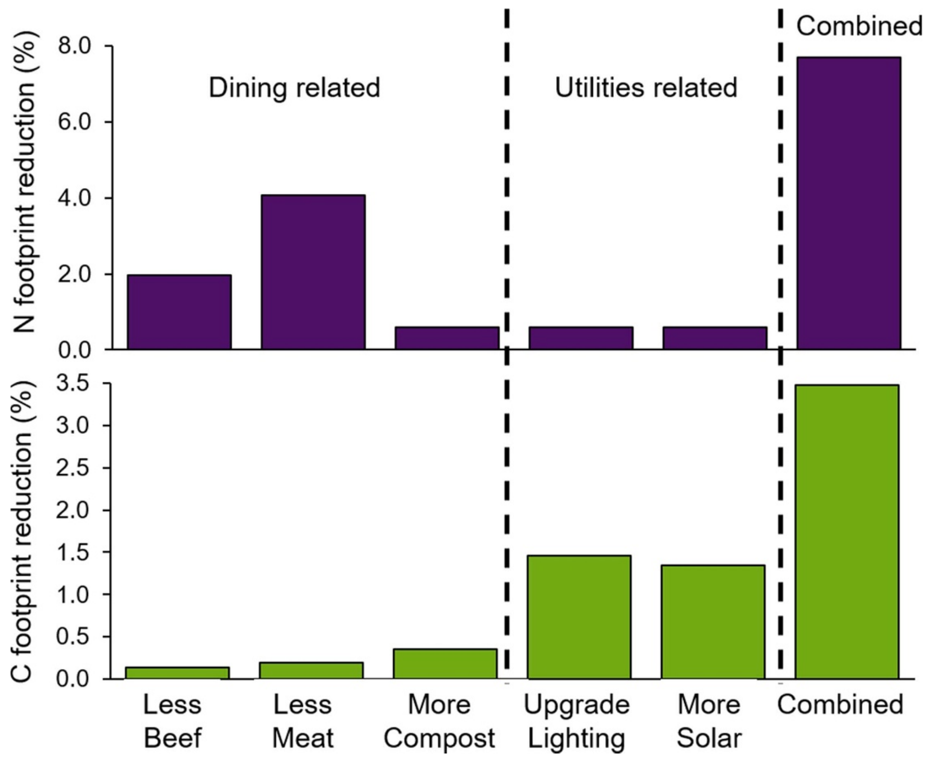

Figure 4. Reductions in the MBL's total nitrogen and carbon footprints under modelled emission reduction strategies presented as per cent reduction.

MBL's managers. Among dining related scenarios addressing food purchased, there is a slight increase in the footprint of plant items but this increase is greatly outweighed by the decline in the footprint of meat (figure 2(B)). The 'Less Beef' scenario resulted in a 2.6% reduction in the nitrogen footprint of food purchased (figure 2(B)) and is considered highly feasibly by the dining manager (table 1). The dining manager identified the 'Less Meat' scenario as moderately feasible but this strategy reduces the nitrogen footprint of food purchased by 5.7% (table 1, figure 2(B)). Both modelled utilities related strategies, 'Upgrade Lighting' and 'More Solar', each reduce the nitrogen footprint of the utilities sector by 7.3% (figure 3(A)). The 'Upgrade Lighting' scenario is considered highly feasible while MBL's facility managers consider the 'More Solar' strategy only moderately feasible (table 1).

All five individual strategies also achieve reductions in the MBL's total nitrogen footprint. The 'Less beef' strategy reduces the total nitrogen footprint by 2.0%, 'Less Meat' 4.1% and the 'More Compost' strategy reduces the overall nitrogen footprint by <1% (figure 4). Though the 'More Compost' strategy achieves the smallest footprint reduction it is considered highly feasible by the MBL's kitchen manager (table 1). Though the utilities-related strategies modelled in this paper effectively reduced the nitrogen footprint of the utilities' sector, they both reduce the overall nitrogen footprint by only 0.6%. When all five strategies are applied simultaneously in the 'Combined' scenario, the overall nitrogen footprint is reduced by 7.7% (figure 4).

All five individual scenarios also reduced the carbon footprint of their respective sectors as well as the MBL's overall carbon footprint. The 'Less Beef' and 'Less Meat' strategies reduced the carbon footprint of food by 3.8% and 5.2% respectively (figure 2 (C)). The 'Upgrade Lighting' and 'More Solar' strategies reduced the carbon footprint of the utilities sector by 6.4% and 5.9% respectively (figure 3(B)). The 'Less Beef' and 'Less Meat' strategies reduced the MBL's carbon footprint by 0.1% and 0.2% respectively (figure 4).

The 'More Compost' strategy reduced the total carbon footprint by 0.3% (figure 4). The utilities related strategies are more effective at reducing the MBL's total carbon footprint. The 'Upgrade Lighting' and 'More Solar' strategies reduce the MBL's carbon footprint by 1.5% and 1.3% respectively (figure 4). As with nitrogen, the maximum carbon footprint reduction is possible when all strategies across sectors are applied simultaneously. A maximum 3.5% carbon footprint reduction is possible via the combined strategy (figure 4).

6. Discussion

Based on the results of this study, the MBL can utilize feasible low-effort strategies to reduce its total nitrogen footprint by up to 7.7%. This is a substantial reduction, particularly given that all modelled strategies can be implemented without major changes in current operations and without substantial inputs of money or manpower. These results support the efficacy of a 'bottom-up' approach to addressing nitrogen emissions, particularly where institution-wide commitments and large-scale changes are not feasible. Some institutions that have taken a 'top down' approach often commit larger nitrogen footprint reductions (e.g. 25% reduction by University of Virginia Nitrogen Action Plan, Castner *et al* 2017). However, studies at other institutions have found that low-effort strategies can achieve nitrogen footprint reductions in the range of 5%–18% (Barnes *et al* 2017, Castner *et al* 2017, de la Reguera *et al* 2017). Our results support those later studies. Based on these studies and our results, 'low-effort' strategies are a critical to both a top down and bottom up approach to nitrogen emission reductions. Substantial nitrogen footprint reductions require extensive and expensive upgrades that are not currently feasible at small institutions like MBL (Leach *et al* 2013, Castner *et al* 2017). However, a bottom up approach can effectively reduce nitrogen emissions with little effort on the part of an institution. These strategies can, and should, be applied while the institution builds capacity to make larger changes to its operations and can serve as proof of concept for actions to bring down emissions in some sectors while more ambitious and detailed strategies are developed. They can also help publicize actions among the larger community and promote acceptance of the applied and planned measures by users.

The individual strategies modelled in this study fall along a spectrum of both effectiveness and feasibility. Maximum footprint reductions were achieved when all strategies were applied simultaneously highlighting the importance of pursuing reduction strategies across sectors when employing a bottom-up approach to footprint reduction. For example, the 'Less Meat' strategy was the most effective individual reduction strategy modelled, reducing the institution's total nitrogen footprint by 4.1%. This is a substantial reduction given that this strategy models a relatively small change in operations, reducing meat served by only 10%. However, our managers' feasibility assessment revealed that despite being the most effective individual reduction strategy, reducing the amount of meat served is less feasible than substituting beef with other meats and increasing composting. The dominance of food in the total nitrogen footprint means targeting utilities emissions is a less effective individual strategy to reduce the MBL's total nitrogen footprint. Though the utilities related strategies modelled in this paper effectively reduced the nitrogen footprint of the utilities' sector, they both reduce the overall nitrogen footprint by only 0.6%. However, the 'Upgrade Lighting' scenario, like the 'More Composting' strategy, has the advantage of being highly feasible and realizing emission reduction with this strategy will require little effort on the part of the institution. Based on these results it is worthwhile for the MBL, and similar institutions, to pursue all feasible reduction strategies across sectors in order to achieve the maximum total footprint reduction with the least amount of effort.

Beyond supporting the efficacy of a 'bottom-up' approach to addressing nitrogen emissions, this study highlights the importance of direct and sustained engagement with stakeholders in this process. Some studies have modelled the impact of relatively low-effort changes, including substituting beef with chicken or meat with legumes, and reducing food waste (Barnes *et al* 2017, Castner *et al* 2017, de la Reguera *et al* 2017). However, some of these strategies might not be entirely realistic, and in some cases practically unfeasible considering current and future institutional capacities, resources and needs. In our study, low-effort strategies were designed and their feasibility evaluated by department managers, who are best situated to know what low-effort looks like in their departments. For this reason, we feel the results of this paper provide a more realistic and effective roadmap for the MBL, and institutions like it, looking to reduce their nitrogen footprint through feasible low-effort strategies.

Furthermore, engagement with department managers revealed two important considerations in designing effective nitrogen reduction strategies. First, most individuals we spoke to were primarily interested in reducing the institution's carbon emissions thanks to broad interest in reducing higher education's role in climate change. Many managers had not considered nitrogen emissions or the institution's nitrogen footprint. This is often the case at institution's assessing their ecological impact, carbon is the primary focus and nitrogen is added as an afterthought (Leach *et al* 2013, Barnes *et al* 2017). Our work supports previous research that shows the intersection of global carbon and nitrogen cycles can be leveraged to reduce nitrogen pollution (Barnes *et al* 2017, Castner *et al* 2017). Reduction strategies that fulfill managers' goal of reducing carbon emissions while simultaneously reducing nitrogen emissions are extremely attractive (Leach *et al* 2017). In this case, presenting both carbon and nitrogen footprints to department managers supports the need for implementing reduction strategies in different sectors. If the MBL were to only implement modelled strategies related to food purchased, it would miss smaller nitrogen reductions and associated carbon emission reductions from utilities related strategies. A coupled nitrogen–carbon approach to engaging with stakeholders can serve to double the incentive for a single change in operations.

Second, explicitly considering the role of money is essential in a low-effort approach. In all of our conversations with department managers, economic considerations behaved almost like a third 'financial footprint'. The reality at MBL, and elsewhere, is that department managers' top priority is the institution's bottom line. In selecting which strategies to model and which to reject we took great effort to ensure we only modelled options managers felt were realistic. That meant feasible with the limited manpower, time, and importantly, finances stakeholders currently have at their disposal. Cost defines where on the feasibility spectrum the five strategies modelled fall. Managers in the dining and facilities departments are already implementing some of the strategies modelled in this paper including more composting and upgrading campus lighting. Both of these strategies require some upfront cost but will either save the institution money year over year ('Upgrade Lighting') or keep current costs the same ('More Composting'). Serving less beef and less meat in the dining halls is feasible but will require a commitment from the dining manager. These approaches are unlikely to affect the total cost of food served compared to business as usual. Finally, the 'More Solar' strategy seems to be the least realistic strategy as it will require an annual monetary commitment to purchase the RECs. In all cases, money was one of the most important considerations in whether or not a strategy was feasible at the MBL. This study found that explicitly discussing the cost of implementing emission reducing strategies was essential to developing strategies stakeholders felt would be successful. Considering upfront cost and future savings as an additional co-benefit further strengthens the case for implementing emission reduction strategies.

In summary, our results showed that a 'bottom-up' approach to reducing emissions can be an effective way of reducing an institution's nitrogen footprint, but stakeholder engagement is absolutely essential to ensure proposed strategies are feasible given the constraints at a specific institution. Strategies that can reduce both nitrogen and carbon emissions while also saving money are most likely to be successful. Through this low-effort, bottom-up approach it is possible to achieve footprint reductions with little effort or commitment on the part of the institution at large, and this reductions can serve as proof of concept for some actions to reduce emissions in some sectors while more ambitious and costly strategies are developed.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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