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Practical pedagogy for embedding ESD in science, technology, engineering and mathematics curricula

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Abstract

Purpose – The purpose of this paper is to review and highlight some recent examples of embedding education for sustainable development (ESD), within science and related curricula in ways that are meaningful and relevant to staff and students and reflect on different embedding strategies and discourses.

Design/methodology/approach – A review of recent selected UK and international teaching and learning practice drawing on an expert workshop and link to wider debates about student competencies and embedding ESD in the curriculum.

Findings – There are a number of practical ways of bringing sustainable development into science, technology, engineering and mathematics (STEM) related subjects. Successful implementation requires linking teaching activities to the core activities of the STEM discipline. Reformist approaches to curriculum re-orientation are more likely to be successful than calls for radical, transformational models.

Practical implications – Embedding ESD into the core curricula of STEM subjects is potentially difficult. This paper highlights practical ways of doing this which can be adopted and introduced within the mainstream of STEM curricula and have a greater chance of being taken up than bolt-on approaches.

Originality/value – The treatment of ESD in STEM subjects is relatively under-developed compared to social sciences, humanities and subjects allied to environment. The economic and social significance of STEM subjects means that STEM-related subjects are integral to sustainable development and therefore STEM education must be re-oriented to sustainable development.

Keywords Education, Sustainable development, Sciences, Curricula

Paper type General review

Introduction

Teaching and learning with regard to science, technology, engineering and mathematics (STEM) subjects is of great relevance to sustainable development. The scale of their student numbers within many universities makes them a crucial target for any "greening the campus" or campus sustainability initiatives. The careers of STEM students when they leave are also likely to provide many opportunities to contribute to the research and innovation which most discussion sees as essential to the creation of greener lifestyles and technologies (although, as discussed below, there may be disagreement about preferred research and innovation options). People with STEM backgrounds are also likely to have a considerable influence on broader public and policy debates. Hence, greening STEM is a vitally important topic.

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This is especially true of the UK because academic science and technology capacity is seen as an important national competency; national policy agendas are stressing the need for better understanding of, and innovation to respond to, sustainability challenges; and there are over 100,000 STEM students in its universities.

In this paper, the authors examine some recent British and international experiences in Greening STEM, based on examples presented at, and discussion within, an expert workshop organised by the authors in April 2009. The purpose of this paper is to:

- briefly review challenge to embedding ESD within STEM;
- highlight and discuss some recent UK and international examples to promote ESD within the STEM learner experience;
- discuss the initial process of embedding ESD within STEM curricula within one University setting; and
- discuss the challenges of more radical, or scaling up of such, approaches within STEM.

1. Challenge of embedding ESD in STEM curricula

STEM subjects are a particular case of the application of education for sustainable development (ESD). This aims to increase student awareness about the linkages between their subject and sustainable development; the potential impact and contribution their activities can make to its achievement; and the development of competencies that they can carry forward in their careers where they have the potential to make significant differences to people and the planet. Such an ambition accords with the vision of the UK higher education (HE) funding bodies, one of whom has stated that that:

> Within the next 10 years, the higher education sector in this country will be recognised as a major contributor to society's efforts to achieve sustainability – through the skills and knowledge that its graduates learn and put into practice (HEFCE, 2005).

HEFCE does not specify what those skills are or the knowledge required but adds:

> HEFCE recognises that it is not within its role to influence the curriculum. However, we can support universities and colleges in producing graduates with the values, skills and knowledge to address sustainable development.

This therefore places the responsibility on institutions to define and promote sustainable development within their teaching and learning which in HEFCE's words "avoids the danger of bolting what some might see as the latest fad onto courses; doing so is more likely to create resentment than real change".

There are many good examples of ESD being incorporated into the curriculum (Coral, 2009; Holmberg and Samuelsson, 2006; Leal Filho, 2009; Roberts and Roberts, 2007; Segalas *et al.*, 2009). Often, this takes the form of relatively minor amendments to a typical curriculum pattern of providing a grounding in core knowledge, across a wide variety of domains, through relatively traditional teaching methods. ESD topics are therefore introduced through occasional special lectures, use of environmental issues as the basis for experiments or exercises and so forth. Coral (2009) highlights a greater range of pedagogical strategies foe embedding ESD in engineering education – ranging from case studies and problem based learning through to role play, back-casting and graphical learning tools. However, a number of studies have identified barriers to greater take up and effective embedding (Adomssent, 2006; Desha *et al.*, 2009; Holmberg and Samuelsson, 2006; Martin *et al.*, 2006; Nicolaides, 2006). Martin *et al.* (2006) in particular identified three key barriers, namely, crowded curriculum, perceived irrelevance, and limited institutional or external stakeholder commitment.

These barriers of course apply to many HE change initiatives and are not unique to ESD. All kinds of curriculum change, innovation and enhancement within HE tend to be complex, difficult to direct and unpredictable in outcome (Bamber *et al.*, 2009). Despite this various studies have pointed to the factors for successfully embedding sustainability within HE, notably the role and attributes of individual lecturers (Ferrer-Balas *et al.*, 2008; Holmberg *et al.*, 2008). Our own experiences in the UK however highlight that outside of engineering and geographic disciplines that engaging science and technology lecturers with ESD is more difficult than within the social sciences and humanities. The reasons for this are discussed in Sections 4 and 5 of the paper. In Section 3, the authors briefly examine some recent examples of embedding ESD within specific STEM curricula.

2. Sustainability within the STEM curriculum – some recent examples

(a) Engineering

A number of STEM courses have introduced environmental and social issues through modifications of existing content, or completely new courses. This has probably been most pronounced in engineering, as engineering activities typically involve consumption of energy and resources, and create changes in the physical environment. The latter is especially true of civil engineering. Examples of change include analyses of renewable energy and other clean technologies; introduction of life cycle or sustainability assessment methods; sustainable design and materials; and systems analysis (Higher Education Academy, 2005). The UK Royal Academy of Engineering has produced a guide and case studies to support these activities and to create:

> [. . .] graduates leaving their (engineering) courses inspired by, and with understanding of, both the concept of sustainable development and the place of their chosen engineering specialism in delivering it, and with relevant knowledge and skills to apply in the engineering profession (Royal Academy of Engineering, 2008).

Fenner *et al.* (2006) offer an eight point framework for civil engineers that defines a problem boundary than that traditionally adopted by civil engineers. In addition to the traditional focus on cost, time and quality the eight points to address the complexity of sustainable development are:

(1) ethical foundations;

(2) future visions;

(3) interlinking scales;

(4) systems context;

(5) holistic financial accountability;

(6) maintenance of natural capital;

(7) efficient co-ordinated infrastructure; and

(8) justice through participation.

A Delphi study by Tomkinson *et al.* (2008) asked 30 UK experts about their views on this topic of engineering ESD. The results were that:

- Social aspects were seen as the main challenge.
- The most important responsibility was raising awareness.
- The most important task was modelling and evaluating SD performance.
- The most highly regarded skill to be fostered by ESD was dealing with complexity.
- The best educational approach was case studies and role play.
- The best measure of effectiveness was evidence of a wider perspective amongst perspectives.

Overall, the lessons from the study can be summarised as below:

- For engineering: the wider perspective is vital; an interdisciplinary approach is important; student-centred approaches work; teamwork can be effective in promoting learning; content should be embedded rather than bolted-on; and assessment needs to be appropriate for different learning approaches.
- For the wider STEM community: the big issue is equipping students with competencies to understand and manage change; there is a need for holistic, systemic approaches; inter-disciplinary working is vital; it is important to encourage students to take greater responsibility for their own learning; the Delphi technique could be used in other disciplines to gauge best practice (James and Hopkinson, 2009).

These ideas have been incorporated by the lead author Bland Tomkinson, into a teaching initiative at the University of Manchester sponsored by the Royal Academy of Engineering. The pilot module was an optional 12-week course. It involved groups of students analysing "wicked" problems collaboratively, and producing a professional report. Academic staff prepared scenarios and marked the reports, whilst post-doctoral students assisted with group facilitation. A total of students, from a range of disciplines, took the course in its first year (2008). The course was highly rated by students and facilitators for its emphasis on a number of competencies including interdisciplinary and team work, communication skills, real world content, etc. and was highly commended in a UK awards scheme for campus sustainability (www.eps.manchester.ac.uk/tlc/sd).

(b) Environmentally responsible laboratory based practices

As noted, environmental and social issues can be part of the curriculum by introducing new content about external topics. There is however another interesting route, which is to use environmental aspects of students' day to day experience as STEM learners. Much of this experience takes place within laboratories, and there is a growing movement focusing on issues of sustainable laboratories, e.g. the US Labs 21 movement and the related UK work of the higher education environmental performance improvement (HEEPI) initiative (Good Campus, 2009; Labs 21, 2009). Geoffrey Bell, citing Don Prowler, an American architect associated with Labs 21, commented that:

> Labs embody the spirit, culture, and economy of our age [. . .] what the cathedral was to the 14th century and the office building was to the 20th century, the laboratory is to the 21st century (Bell, 2008).

Sustainable development is an important aspect of the twenty-first century economy and society, but there is often a disconnect between the aspirations for its achievement which students hear from their institutions, the media and other sources, and the reality of their day to day lives within the laboratory. By and large, and especially when compared to other areas of a campus, this remains a place of very large environmental footprint (e.g. energy consumption up to five to ten times that of an office building per square metre), and limited practical action to reduce it. Labs 21 has shown that some of this footprint can be avoided, in part through a better understanding by users of the ways that their lab activities impact upon the environment. There are also opportunities to bring these insights into the STEM curriculum, by having students develop a competency in reflecting upon and developing strategies to influence activities within their own laboratory.

A good example of how this can be done is the laboratory research and technical staff (Lab RATS) initiative at the University of California, and especially its Santa Barbara and Davis campuses. Much of the Lab RATS work is aimed at lab managers and technicians, with a view to changing their operating practices (University of California, 2009). However, its Co-Founder, Allen Doyle, believes that there are a number of features of relevance to curriculum and learning including:

- the scheme employs student interns to conduct energy and environmental audits of laboratories – which provides them with very valuable experience, as well as identifying opportunities for improvement;
- it takes many actions to raise staff and student awareness, including the importance of closing fume cupboard sashes when not in use, and therefore trains and empowers the next generation of scientists to use resources wisely; and
- raising the awareness of lab managers and technicians, and academic staff, is an important precondition for raising awareness amongst students, as they can be role models, as well as providers of information (James and Hopkinson, 2009).

In the UK, Alzena Wilmot from the University of Aberystwyth has published through the Higher Education Academy BioScience Subject Centre (a body which is funded nationally to promote curriculum innovation) a guide to run existing laboratory practicals more sustainably (Wilmot, 2008). She lists a number of areas to reduce waste and improve resource efficiency including: make sure nothing toxic goes down the drain, encourage group rather than individual experiments to minimise chemicals used, avoid leaving equipment running unnecessarily, keep handouts to a minimum, don't throw away equipment unless completely broken or damaged beyond repair.

Her colleague Gwynne-Jones has also shown that poor lab practices can be highly wasteful (Gwynne-Jones and Wimott, 2009). Overnight energy wastage through inappropriate use of standby on lab equipment ranged up to 201 kWh for a bench autoclave. He identified a list of opportunities for more sustainable lab practices and possible barriers to such adaptations (Table I).

Gwynne-Jones also surveyed 102 bioscience researchers on their attitudes towards such initiatives (reported in Hopkinson and James, 2009). He found that:

- About 78 per cent of respondents believed that a researcher who is domestically sustainable does not offset unsustainable behaviour in the lab.

- When asked about the best means of motivating environmental improvement a majority of both male and female respondents ranked monetary/other benefits and an internal staff member dedicated to sustainability the highest, and awareness campaigns and posters the lowest.
- However, a lab energy campaign in four labs for 13 weeks before and after a short energy campaign found significant reductions in lunch hour and overnight energy wastage in the two labs where there had been a campaign and very little saving (or increase) in the two control labs – suggesting awareness campaigns do work and that perceived barriers are not always what prevent sustainable behaviour.

The study concluded that institutions wanting to implement sustainability should consult with all participants and target approaches around their needs; provide appropriate training; set measurable targets and provide evidence of achievements; and provide appropriate rewards for good performance.

(c) Environmentally responsible fieldwork practices

Many STEM subjects also involve field work away from the host institution – indeed the ability to undertake field work forms a key competency in many applied and research led STEM courses. As with laboratories, fieldwork is rarely discussed and often forgotten contributor to the environmental impact of teaching and student learning. Wilmot (2009) highlights that field trips can be one of the most valuable and memorable learning experiences for undergraduates. They can also have a high environmental impact. She outlines a number of ways in which field work can be made less resource intensive and generate greater student and staff awareness and action to reduce potential impacts. This includes timing of visits, form of travel, accommodation choices, levels of damage created by fieldwork itself, addressing waste and recycling and food choice. She advocates that students are involved in choices and decisions with regard to fieldwork design, and that after the activity students and staff write about the outcomes to raise awareness and encourage others to follow.

Such actions can be facilitated by the carbon footprint calculator for fieldwork which has been developed by Ribchester *et al.* (2008). The tool requires data on travel,

Opportunity	Barrier
Wash and reuse wherever possible	Initial cost and cleaning time
Turn off equipment when not in use	Lack of organisation between users
Choose energy efficient equipment	Initial cost
Recovery of solvents	Time, purity
Making solutions in bulk	Storage issues, contamination, stability
Preferential use of least toxic options	Cost plus research required
Signage to categorise waste	Significant reorganisation
Plastic, paper, glass, organic recycling	Time plus concerns about contamination
Engage students in recycling	Could create more work

Source: Wilmot (2008)

Table I. Opportunities and barriers associated with reducing environmental impacts of bioscience practicals food, waste and energy. The developers of this tool argue that students themselves have to be involved in the data collation to make this exercise meaningful and effective. The challenge of collecting accurate data, and of understanding different interpretations of the topic's importance, and the environmental impacts of different choices, can provide a very useful learning experience. They present the calculations from three residential field trips to Spain, Norway and within the UK, with the Spanish trip being four to six times more carbon intensive that the other two and interestingly the Norway trip being less carbon intensive than the UK trip (owing to the choice of accommodation). Student feedback indicated heightened awareness and interest in carbon foot printing, and longer-term behavioural changes after completion of the calculations.

These examples highlight a practical pedagogy linking aspects of resource efficiency and environmental impacts through mainstream, everyday laboratory activities, without any major adjustments or adaptations to existing curricula or science programmes. Although limited in scale, such initiatives do have the potential to promote and develop student awareness about the impacts of everyday choices and actions in laboratory activities, and to build broader competencies in environmental responsibility. At a practical level, such activities could be easily built into academic activities, e.g. through laboratory inductions in the same way that health and safety and risk assessments are now standard practices, or into the risk assessments of field trips and such activities which are now a standard UK practice.

(d) Re-thinking practical experiments

When chemistry graduates seek employment their jobs are often in activities and sectors that are greatly affected by environmental concerns and regulations. The chemical industry itself has a poor reputation amongst many environmentalists, and its products –"chemicals!" – are often seen as inherently suspicious and threatening by the general public. This is reflected in a plethora of regulations and initiatives, including the recent European REACH (registration, evaluation, authorisation and restriction of chemicals) directive and supply chain initiatives by many retailers. These negative environmental perceptions are reinforced by the fact that 90 per cent of organic chemicals still come from oil, resulting in a very high carbon footprint.

The Green Chemistry movement represents a challenge to these activities, by championing – in its more radical manifestations – the complete replacement of current industrial activities with new, renewable, raw materials, new conversion processes (e.g. low temperature catalysis) and new products (e.g. biodegradable plastics). The movement now has a significant institutional base. In the UK, for example, there is a Green Chemistry Centre of Excellence at the University of York, part of whose activities are running a Green Chemistry Network, which has over 1,500 members (Green Chemistry, 2009). This radical agenda is starting to be reflected in curriculum at the postgraduate level, with several new Green Chemistry masters courses. However, changes to undergraduate chemistry are more limited, with very few courses having material on the topic (Hopkinson and James, 2009).

Change at undergraduate level is occurring, however, with several initiatives to develop support materials for practicals to demonstrate green chemistry principles. In most cases, these are intended to fit into existing curricula without requiring major changes. Thus, the UK Royal Society of Chemistry has sponsored a book providing procedures, teaching notes, etc. for green chemistry experiments such as clean and efficient synthesis of 4-aminobenzoic acid from 4-nitrotoluene; extraction and conversion of limonene to terephthalic acid via *p*-cymene (Hardy and Clark, 2009). A collaborative project between the University of York-based Green Chemistry Network and the University of Bradford Chemistry Department is also developing similar materials to encourage life cycle thinking amongst students and develop their competency in systems thinking. This involves taking standard undergraduate practicals using solvents (see below) and then providing a green chemistry variant so that students can compare both their performance in use (yield) and their differing environmental impacts across the full life cycle (manufacture, use and disposal). For example, a standard undergraduate practical involves preparing silver complexes using various methods. One stage requires vacuum filtration and washing with three solvents, water, ethanol and ethoxyethane. In the modified experiment only one solvent will be used to compare overall efficiency. Students will be provided with background on the toxicity and environmental impacts of the different solvents as a basis for judging the benefits of reducing solvent usage versus changes in efficiency.

These approaches are intended to integrate "ecological systems thinking" into traditional chemistry activities in ways that are meaningful, forward looking and relevant to future employment prospects. They require students to apply traditional analytical and evaluative skills and competencies but within a broader frame of reference. Of course, this is still some way from the more radical questioning of the entire approach to organic chemistry which is implicit in the green chemistry vision, but it does provide a stepping stone towards it.

3. Embedding ESD in STEM curricula across a university – the ecoversity initiative at the University of Bradford

Ecoversity is the name given to a whole university initiative which aims to embed sustainable development into the living and learning experience of all students and staff (www.bradford.ac.uk/ecoversity). Started in 2006, the initiative has a number of sub-projects including the physical regeneration of the main campuses, embedding ESD in the formal curriculum, enabling student engagement for campus sustainability and promoting culture change around sustainable development. In this section, the authors describe briefly some experiences of working with STEM lecturers in selected areas on ESD.

Our formal curriculum project involves all academic areas undertaking reviews to identify the current levels and scope for enhanced ESD. The aim is to identify ways of infusing ESD in ways that are meaningful and relevant to staff and students. Bradford has a large STEM footprint with over 60 per cent of student enrolled on such courses and nearly 10 per cent of our students on courses linked to pharmacy. Features of our curriculum approach include:

- incorporation of ESD as a strategic corporate aim within our new corporate strategy (2009-2014);
- a course review and approval process that requires all new courses and course subject to five year review to demonstrate how and where they articulate ESD;

- appointment of academic as lead ESD champions to spearhead curriculum change within their academic areas; and
- funding to stimulate and support specific discipline focussed curriculum interventions or development.

Our curriculum work is currently at the end of its second year. The first period has been concerned with review and developing understanding amongst academic colleagues of ESD and identifying opportunities for development. This has not always been easy as the term ESD is unfamiliar to many staff, feels irrelevant to their subject area and lacks support from the professional and accrediting bodies which regulate much of our STEM provision. Bringing a new teaching and learning agenda around ESD to STEM subjects has therefore required using a range of strategies to make progress within specific subject areas or with specific individual or groups of colleagues. One key strategy has been to work with staff champions to look outwards at emergent or recent changes in the ways in which major employers, funders or accrediting bodies are engaging with sustainable development and bringing these to the attention of the internal subject community.

As an illustration, the authors refer to one subject area example – pharmacy. Like many other health science disciplines – and in contrast to chemistry and engineering – this is a subject where the linkages with ESD are not immediately obvious. Students attending the pharmacy programme at Bradford are interested in two career routes – becoming a dispensing pharmacist or working in the pharmaceutical industry. An initial curriculum review as part of an institutional institution-wide programme to embed ESD into the learning experience of all students (Hopkinson *et al.*, 2008) found that most modules and teaching elements were concerned with core scientific principles and method and laboratory experiments, and that there was little or no reference to sustainable development within existing course documentation. However, several modules did cover alternative methods of treatment (e.g. herbal medicine, homeopathy), and in so doing covered the broader social attitudes and trends which were making them popular with many patients. These topics are of course challenging to a traditional science-based curriculum, but the resistance to their inclusion was overcome because of their evident impact on the pharmacy "market", and their potential implications for professional pharmacy practice. Hence, the subject champion, Beverley Lucas, and her colleagues formed the view that a focus on changing professional practice, and the social context in which it is embedded, might also be an effective vehicle for introducing ESD concerns.

A subsequent review examined this issue further (Lucas *et al.*, 2009). It identified an important "lever" for change in a strategic policy document produced by the Department of Health (2008), the Pharmacy White Paper for England. This stressed the central role of pharmacy as a trusted source of information and advice on many aspects of community well being, and envisaged the profession developing into a much broader local role than it had traditionally occupied. Careful thought revealed a number of connections between this and the concerns of sustainable development, e.g. the potential role of climate change in changing the patterns of disease which pharmacists are involved in treating; the need to address health inequalities, specially amongst disadvantaged minorities (Lancet, 2009). These connections, plus research evidence that the manufacture and supply of pharmaceuticals comprises a high proportion of the environmental footprint of Britain's National Health Service, then provided a "pharmacy specific" set of possibilities for modifying the curriculum.

Three recent publications (PharmacyHealthLink, 2009), aimed at pharmacy's contribution to public health and in particular, its role in health improvement and how it can play a more active role in community leadership and sustainable development, were then identified as vehicles for small group exercises and discussion and subsequent student reflection on the relationship of sustainable development to their personal practice, and that of the profession as a whole. The student exercises addressed what role and contribution a practitioner could make in terms of reducing the environmental impacts of pharmacies, and the extent to which pharmacists impact on the well-being and health of patients in their catchment areas.

The feedback and evaluation was very positive – the combination of collaborative, active reflections, and coverage of topics they had not addressed or even thought about on other parts of their course, was generally very well received. About 72 per cent of students found the session worthwhile and stimulating, and a similar number reported that it would impact on their professional activities. One reason for this may have been the pedagogy itself, as the use of small group work and reflective practice were themselves relatively novel in the pharmacy programme. However, it was also the case that most students actively engaged with the content itself. Interestingly, many of them were critical of the materials that had been produced by the Department of Health, and this led to further discussion about what might be more effective.

The experiences from the exercise revealed that even curricula as tightly prescribed and controlled as pharmacy have openings and opportunities for new developments. Similar strategies are currently being undertaken in subject areas such as optometry, biomedical sciences and chemistry. By themselves, however progress within individual modules and lecturers is unlikely to achieve the level or rate of embedding ESD that is frequently discussed but rarely achieved. In our situation, having a top-down framework for ESD, from the Corporate strategy to the course approval and review process (CARP), together with the backing and support of key leaders in the institutional teaching and learning framework (e.g. Deputy Vice-Chancellor teaching and learning) has been crucial to reducing the number of escape routes and hiding places that academic colleagues are able to use when new curriculum change initiatives are introduced.

4. Discussion and conclusions

Some of the examples cited in the previous sections might be seen as some within the ESD community as relatively modest – forming what some authors have referred to as an "accommodating" strategy as opposed to a "transformational" approach (Sterling and Witham, 2008). There are different perspectives and discourses which can be used to describe the extent, and ways, in which the concerns of sustainable development are articulated within and form the underpinning values of a curricula. Dryzek (2005) identifies a number of different "sustainability" discourses, but groups them into four main types, based on:

- their attitudes towards the current economic and industrial system (seeking to "reform" it, rather than seeking a more "radical" transformation); and

- their action focus, with a distinction between "prosaic" (relatively bounded and focused on specific issues) and "imaginative" (more holistic and wider ranging) approaches.

Dryzek characterises the four types of discourse generated from these distinctions in the following way:

(1) "sustainability" (imaginative and reformist);

(2) "environmental problem solving" (prosaic and reformist);

(3) "green radicalism" (imaginative and radical); and

(4) "survivalist" (prosaic and radical).

The examples cited above can be classified, in the terminology of Dryzek (2005), as reformist. They do not fundamentally challenge the status quo (accommodating), but are essentially making incremental changes to course content, and introducing pedagogic practices into STEM that have long been mainstream in humanities and social sciences. This even appears to be true of Green Chemistry which, despite its underlying radical challenge to the status quo, is operationalised at undergraduate level through relatively modest changes in laboratory practice. Some may believe that this reflects a failure on the part of academics, and that we remain a long way from the "promised land" of green radicalism, which is required in order to truly grapple with the sustainability challenges of our time. However, an alternative explanation is that many STEM academics and students, for reasons of both disciplinary tradition and personal psychology, are less receptive to ways of thinking that fundamentally challenge existing practices, especially when these do not appear to have immediate practical applications. Certainly, the authors' experience is that many STEM academics and students find sustainable development to be a nebulous and partly ideological concept, and if forced to respond to it can be antagonistic and negative. Whilst some may see this as unfortunate, it is perhaps a reality which has to be taken on board within many institutions, and worked with or around in present circumstances.

In these circumstances, ESD-related changes to STEM curricula are most likely to succeed when they clearly relate to core scientific and technical competencies such as, analytical rigour, critical thinking, and empirical observation and testing, and build on – rather than work against – existing disciplinary, departmental and teaching and learning cultures. The challenge is to identify and embed creative and innovative teaching and learning activities within traditional laboratory, field work and problem solving pedagogies. Such strategies reflect wider discourses and strategies for influencing and enhancing teaching, learning and assessment (Pennington, 2003). Examples include linking concerns about resource utilisation and wastage to good experimental practice procedures in disciplines such as chemistry, or to established approaches such as lean manufacturing in engineering. Widening the horizons of subject areas to address the complexity of sustainable development as Fenner *et al.* (2006) propose, however, requires consideration of more than just technical, environmental issues but should include also values, ethics, wider social and systems viewpoints and longer time horizons.

One positive conclusion is that active, practical and collaborative pedagogies of the type manifested in all our examples can produce positive student feedback, as well as demand from students for more teaching of that form and style. Students also report feeling more skilled and employable. Furthermore, teaching activities involving laboratory practicals or audits require new forms of collaboration between academics, students and laboratory staff which can help to raise the profile and academic contribution of highly qualified laboratory staff. Any activities that can promote and achieve reductions in the environmental impact of laboratory operations also generate a further sustainability dividend for a university, helping to improve its sustainability performance and reduce costs and liabilities.

Another positive conclusion is that ESD-related changes to STEM can be synergistic with other actions to increase student employability, and to develop their professional practice knowledge and skills. Teaching and learning around professional practice is common in areas such as health studies, and, increasingly, medicine, with students being encouraged to reflect on placements, and to work with patients in real or simulated settings. Such reflective practise is less common in other STEM subjects, partly owing to the subject area being seen as more "objective", with fewer direct links to people. However, the Bradford pharmacy example demonstrates that it can potentially be transferred to these areas.

Change is not always rapid in university curricula and innovations may attract resistance and opposition for a variety of reasons (Martin *et al.*, 2006). However, many examples show that, with the right strategies, change is possible (Mulder and Jansen, 2006). The same is true of change to achieve ESD in STEM. Our examples have suggested a number of different ways in which this can be addressed. The common "success factor" they seem to share is an active, enquiry (problem-based) learning model – which encourages students to take critical and reflective stances on the ideas/data and issues they are generating or being presented with – tempered by a practical concern to relate closely to the core competencies and concerns of their discipline.

Such strategies reflect wider discourses and strategies for influencing and enhancing teaching, learning and assessment (Pennington, 2003). The challenge of how to move from successful good practice at the level of the individual or unit of teaching – such as those described in this paper-to programme, faculty or wider subject level is itself a topic for a further paper. Our own experience in our own institution is that wider infusion and embedding of the type described requires four elements. First a top down institutional vision and academic policy for ESD together with an academic implementation strategy. In our case, this is achieved through ecoversity and a curriculum framework which requires all courses articulate ESD within the curriculum. Second, and in parallel a bottom up approach which supports, incentivises and identifies good practices in ESD in STEM subjects and seeks to spread this work within course teams. Third, evidence of professional, employers or accrediting bodies taking ESD as an important issue and thereby adding pressure on university staff to respond and demonstrate how they are building such requirements into their courses. Fourth, an institutional, educational and curriculum architect and entrepreneur who can work across disciplines and handle a wide array of potential minefields and conflicts that arise whenever academic staff are asked to consider curriculum change. How these elements are combined and implemented within an institution will vary depending on the history and culture of the specific department or faculty.

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