This is a repository copy of *Engaging students with plant science: the plant science TREE*.

Article:

Letters

Engaging students with plant science: the Plant Science TREE

Introduction

In this paper, we show how a single web resource can engage a wide student audience with plant science. Developed by the University of Leeds, UK, the Plant Science TREE (Tool for Research Engaged Education (www.tree.leeds.ac.uk)) is an online teaching tool giving access to online research lectures, downloadable lecture slides, practicals, movies and other material on topical plant science to support lecturers in their teaching. The Plant Science TREE complements the annual Gatsby Plant Science Summer School, which has already succeeded in engaging undergraduates with plant science (Levesley *et al.*, 2012). Both initiatives were instigated to address the decline in student numbers in plant science (Sundberg, 2004; Stagg *et al.*, 2009; Jones, 2010; Drea, 2011) at a time when there is concern that future demand for plant scientists will not be met (The Royal Society, 2009). The causes of this decline are unproven but may be the result of a combination of factors including, greater preference by students for animal and medically-based degrees, disengagement from plant science at school, and narrowing of plant-based undergraduate curricula. Where the summer school aims, by face-to-face contact, to inspire relatively small numbers of high-achieving students to consider plant science as a career option, the Plant Science TREE aims to reach a much larger, more diverse global audience through the use of web technologies.

By creating, sharing and bringing together engaging plant science educational resources in a one-stop, easy to use repository, we aim to leverage quality research led resources, reduce the workloads of individual educators through a reduction in duplicated effort, broaden the learning opportunities for students and importantly engage students in plant science and research in general, especially in areas where expertise is becoming limited.

The swift advancement of web technologies has provided opportunities for learners to access enormous quantities of external information on virtually any topic. Several studies suggest that digital technology, when used together with traditional teaching methods, such as in a blended learning approach, can enhance lectures, increase student interest and knowledge in science (O'Day, 2007; Greenfield, 2009) and even lead to accelerated learning (Lovett *et al.*, 2008). Increasingly, educators have an essential role in guiding students in their use of online resources, ensuring that the information they receive is accurate and relevant, as well as to inspire students by teaching topics *de novo*. However, the selection and validation of the vast array of resources and their

integration into undergraduate curricula can be time-consuming. Furthermore, the number of current research-informed academic resources addressing certain disciplines for example aspects of plant physiology, weed science, entomology, aspects of pathology and soil science is limited, even though these have been identified as vulnerable niche skills (The Royal Society, 2009; Food Research Partnership Skills Sub-Group, 2010; Horticulture Matters, 2013). Unless more students are attracted to acquire knowledge and skills in these topics, there is a risk that valuable knowledge will be lost as academics retire. A recent survey of over 300 UK plant scientists identifies education and training as the single most important risk to the UK's ability to address global challenges such as food security and climate change (UK Plant Science Federation, 2014).

The UK plant science research community already contributes to various education and outreach programmes aimed to inspire interest in plant science, including those organized by the Gatsby Charitable Foundation (Gatsby Plant Science Programme, 2014), The UK Plant Science Federation (2014) and its member organizations and other institutional efforts. Consequently, we were able to seek support and contributions from research academics who were already good communicators of plant science to their own students. Research academics who are passionate about their teaching, were invited to champion a plant science discipline, encourage their colleagues to participate and lead subject specific meetings that covered plant development, lifecycles, reproduction, plant structure, cells, genes and proteins, signalling, metabolism, evolution, abiotic environment and biotic interactions. Academics shared and reviewed their lecture slides, selected essential content and built a structure for their respective subjects. The innovative hierarchical TREE structure was thus created and forms an easy to use browsable framework for digital content with the advantage of the structure defining important areas in modern plant science. Modern web technologies, such as open source mind mapping software, were employed in the construction of the TREE to provide a smooth and extensive browsing experience which help the user find relevant content quickly and may even lead to a serendipitous find.

The TREE supports a wealth of research-led educational resources from over 90 contributors to date; resources may be freely downloaded and have been licensed for educational use. A key feature of this teaching tool is that it highlights current plant science research. Where a lecture slide is derived from a research paper it is linked to the original source for reference. Uniquely, the TREE holds a collection of 42 online research lectures that were delivered at the annual Gatsby Plant Science Summer Schools between 2006 and 2013 and were successful in engaging undergraduates in plant science (Levesley *et al.*, 2012). The lectures cover a broad range of cutting-edge plant science research that address globally relevant applied initiatives as well as curiosity-driven research. They are pitched at a level to engage undergraduates early in their degree studies, highlighting many of the unanswered

questions and providing insight into how discoveries are made and science is carried out. They have been edited into an interactive format for online delivery that shows the speaker, their slides and the capacity to search or select any part of a lecture through slide thumbnails and search facility.

A number of good quality digital resources are provided elsewhere by various publishers (e.g. Teaching Tools in Plant Biology from the journal *The Plant Cell* and instructor resources supporting text books e.g. *Plant Biology* from Garland Science (Smith *et al.*, 2009). It is our experience (Levesley *et al.*, 2007) that academics also value the opportunity to build their own lectures from individual digital assets rather than pre-packaged learning materials and they value the availability of specific slides, images, films, journal figures, etc. from trusted sources that they can incorporate into their teaching. The intuitive TREE browsing structure allows exactly that and aims to simplify the adaptation and re-use of peer selected plant science educational resources. Current content is by no means exhaustive but forms the foundation for key areas in plant science and an online 'upload' facility allows users to contribute their teaching materials to the repository so that it may continue to grow.

Feedback from academics highlighted the value they placed in keeping current with developments in plant science (Levesley *et al.*, 2007). In response, we developed the 'Plant News' with RSS feed and search facility, which links to news articles, research articles, podcasts and videos of current developments and breakthroughs in plant science from leading journals and the media. The Plant News searchable database forms part of the Plant Science TREE and aims to facilitate the use of plant news stories in teaching.

Here we describe the creation, technical aspects and evaluation of impact of the Plant Science TREE on learning and teaching practices and on student engagement. Through web statistics, user registration data and online surveys we evidence the audience reach and profile as well as patterns of use and preferences of both educators and learners. We present a case study involving academics and undergraduates from four UK universities that focuses on the use of online research lectures as a learning tool and discuss the value of these as a means to engage students in plant science and research in general.

Materials and Methods

Technical development

The Plant Science TREE digital repository system consists of an application built in PHP 5.3 (The PHP Group) running on an Apache 2.2 web server (The Apache Software Foundation) on a Redhat Linux server. Data is stored in a MySQL 5.5 cluster (Oracle Corp.). The system accommodates delivery of a variety of educational resources (online lectures, lecture slides, videos, images, documents, web links) and supports most file formats. An innovative hierarchical TREE structure, based on mind mapping open source software, forms an integral feature of the TREE and provides a browsable framework for content. The system is scalable and consists of a user interface and an administrator side. The administrator side has been designed to accommodate content upload, editing of content metadata and of the TREE structure. The system accommodates an upload facility

that allows users to deposit and therefore contribute resources to the TREE, all uploaded content is verified by a project administrator before going live. The Plant Science TREE requires registration and login for full access to all resources, however, open access resources may be viewed without registration.

Online research lectures

The research lectures, available through the Plant Science TREE, were filmed at the Gatsby Plant Science Summer School. Each filmed lecture is cut into short clips, each representing a single slide and edited into an interactive online lecture using Articulate Studio (09 and 13; Articulate Global Inc., New York, NY, USA), that shows the speaker, their slides and the capacity to search for or select any part of a lecture using slide thumbnails or search facility. The research online lectures may be viewed on a desktop or laptop through an Adobe Flash Player enabled web browser and more recent research lectures (from 2013) have been published to multiple formats so learners can view these on their desktops, laptops, iPads, and android mobile devices.

Copyright

Publishers and authors of digital resources to be held within the Plant Science TREE repository were approached and permission sought to license for educational use. Content was licensed through Copyright Clearance Centre RightsLink, or through a bespoke licensing agreement drawn up by the University of Leeds. Permission from the copyright holders was also sought to display all lecture slides used in the online research lectures. The author and copyright holder is acknowledged in the supporting information associated with each downloadable digital resource. The Plant Science TREE 'terms and conditions of use', drawn up by the University of Leeds, require all users to attribute the author and copyright holder on every use of the digital resource. Users are free to download and re-use materials for educational non-commercial purposes, resources may be downloaded to their own institution's virtual learning environment or re-used in their lectures or other teaching activities, but they are not openly available for redistribution. The TREE now supports an online upload facility where users may contribute and share their content under a Creative Commons license (Attribution-NonCommercial-ShareAlike 3.0 Unported (CC BY-NC-SA 3.0)). This approach has been adopted to reduce costs, but does mean that future content is restricted to materials authored and owned by the contributor. Many contributors and publishers prefer their materials to be restricted to 'registered users' only, hence, although materials are free to download and use for educational purposes, all users must first register with the Plant Science TREE and access the materials by logging into the site, where usage can be monitored.

Impact study

The impact of the Plant Science TREE on learning and teaching practices was evaluated based on measurable indicators of impact as defined by Jisc (formerly known as Joint Information Systems

Committee, JISC) (Jisc, 2012); these include frequency and patterns of use of a resource; the extent to which it is useful, recommended or linked to; and audience reach. The following methods were employed to gather data for the impact study:

(1) Web statistics provided information on traffic and visitors to the TREE and were employed to assess frequency and patterns of use, downloads and audience reach;

(2) Information from user registration data was used to define the audience profile such as occupation and affiliated institution ($n = 1121$).

(3) Three online user surveys were deployed to collect in depth data on how educators and learners use the TREE: The Online TREE user survey was targeted at all users and where necessary, the data was filtered to collect specific information on educators that is those teaching at tertiary level. The survey was emailed to 1121 users. The Online student survey was targeted at learners, to assess the impact of the online lectures as a learning tool and as a means to engage students into plant science and research. The survey was emailed to 549 undergraduate students from four UK universities. These students were not registered users and hence were not included in the TREE user survey described earlier. The students were additional users for whom registration was not necessary since they had been recommended the resource by their registered university lecturer. The Gatsby Plant Science Summer School survey was targeted at undergraduate students, directly after viewing the live lectures at the Summer School, to obtain a direct comparison between 'live' vs 'online' viewing experience. The survey was given to 160 students at two summer schools (Supporting Information Table S1). In all the surveys, not all respondents answered all questions and the number of actual responses are given in the results section where the relevant data are discussed.

Results

Who uses the Plant Science TREE and why?

At the time of evaluation the TREE supported 1121 registered users from 320 educational or research institutes world-wide. The TREE and Plant News received over 1600 unique site visits per month (57 500 hits per month) from 37 countries, during the evaluation period June 2012–May 2013. The Plant News accounted for 75% of visits from unique sites per month. The profile of registered users is shown in Fig. 1(a) and comprises 34% higher education academics, ranging from Heads of Departments to associate professors and lecturers, and 29% undergraduates, including students recommended the resource by their university lecturer as well as those who heard the lectures live at the Gatsby Plant Science Summer Schools. The remaining 32% comprise a wide-ranging group of professions including researchers, school-teachers and technicians, as well as those involved in the media and other communication and outreach activities.

Web statistics revealed that the summer school online research lectures received over 3000 viewings during the 12 month evaluation period, which accounted for 81% of all downloads during that period (Fig. 1b). The lecture slides and images were also popular and accounted for 12% of downloads (452 per year).
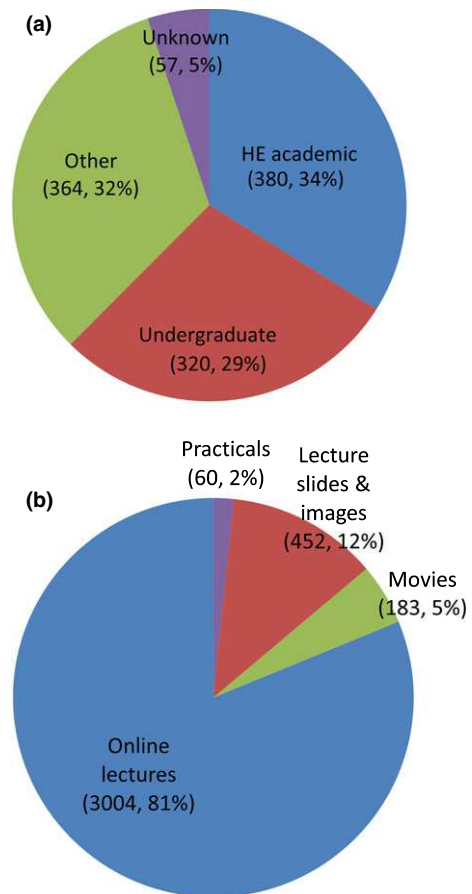

Fig. 1 The Plant Science TREE audience profile and user preferences. (a) Occupation of TREE registered users with numbers and percentages shown in brackets ($n = 1121$). Data were collected from the information provided by users on registration. Responses are shown clockwise as follows: blue, higher education (HE) academics; red, undergraduates; green, other; purple, unknown. (b) Types of resources downloaded by all users from the TREE over a 12-month evaluation period (1 June 2012–31 May 2013) and expressed as number of downloads and percentages of total downloads. Data were obtained from web statistics using Webalizer version 2.01 (http://www.webalizer.org/) and bespoke log file analysis software. Responses are shown clockwise as follows: purple, practicals; red, lecture slides and images; green, movies; blue, online lectures.

An online survey was sent to all registered users to evaluate their use and preferences for the resource. Ninety-seven responses (9% survey response rate) were received from educators, learners, researchers and those working in outreach from 15 countries in Europe, the Americas, Asia and Australia. Of the 39 educators who responded to the question, 85% had downloaded resources. Educators mostly downloaded lecture slides and images followed by online research lectures, whereas learners and researchers mostly viewed the online research lectures. It is worth noting that the user and student survey response rates (of 9% and 8%, respectively) fall within the range expected for an external email prompted survey, for example a recent study found that online surveys generate a response rate of 5% and email delivered 9.3% response rates (ServiceTick, 2012).

Regarding user preferences, 95% of 59 respondents rated the research lectures and lecture slides/images as very valuable or

valuable. From the 29 replies from educators, the most valued resources were the lecture slides/images, movies and animations and the online research lectures, with > 85% of educators rating all of these as very valuable or valuable. Seventy-six percent of educators found the Plant News valuable. Unsurprisingly, the most valued resources amongst undergraduate students were the online research lectures. Of the 22 student respondents, 95% found them valuable and 86% stated that they had viewed an online lecture to learn about a subject and to enhance their personal understanding.

Educators valued the quality of the TREE with all 28 respondents to this question either strongly agreeing (61%) or agreeing (39%) that the resources were of a high standard. Ninety-six percent found the unique TREE browsing structure valuable with users agreeing that the browsing function was a clear, quick and easy way to find relevant content and identify areas of interest. Eighty-nine percent of educators agreed that the resources enhanced their teaching.

Educators who responded to this question (31 replies) reported that they mainly (81%) used the resources to develop or plan a new course, lecture or tutorial, which is supported by web statistics showing that usage peaks at the start of each UK academic term. Other uses include to enhance personal understanding (32%), enhance teaching (32%), or to keep current in developments in plant science (29%).

Our user survey captured narratives of the value of embedding materials, for example many educators stated that they had used the slides and movies in their lectures to explain a concept or as examples of current research; others had provided access to selected online talks for their students to complement their own lectures; others used the slides to provide ideas and structure for their own teaching and others referred their students to the site for further information.

Case study: does the TREE lead to enhanced student learning?

Given the positive feedback from both learners and educators about the online lectures, we undertook a case study to evaluate the effectiveness of the online lectures as a learning tool. Undergraduate students from four UK Universities who had already been directed to one or more online research lectures by their university lecturer as part of their course (Supporting Information Tables S1, S2) were asked to fill in an online survey. Each academic directed their students to different online lectures as further information for diverse bioscience topics covering circadian clocks, biotechnology, cell signalling and photosynthesis. One academic linked the online research lecture to a disclosed exam essay question. The case study involved undergraduate students from year groups one to three on a range of programmes of study and studying diverse subjects (Supporting Information Table S2). Forty-two students (8% survey response rate) responded to our survey, but viewing statistics collected through the University of Leeds virtual learning environment suggest that a large proportion of students viewed the online research lectures when directed to do so by their university lecturer. Specifically, these viewing statistics indicated that more than a third of the students from two undergraduate

programmes of study viewed one recommended online research lecture and between 50% and 60% viewed a second recommended lecture. Although a 'view' may not equate to viewing the whole lecture, it does indicate a curiosity to find out more (see Supporting Information Table S2).

Figure 2(a) shows how lectures are presented online. Viewers can see and hear the lecturer (top left panel) and view the slides (right panel). They can also select parts of the lecture to view (bottom left panel). We were interested to know whether the experience of viewing the lecture online matched the experience of hearing the
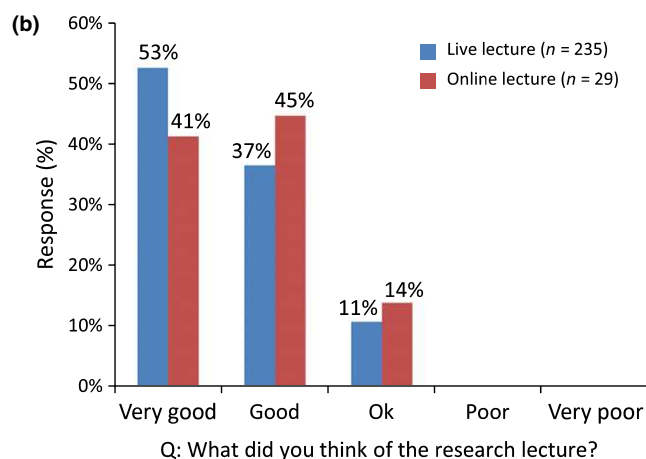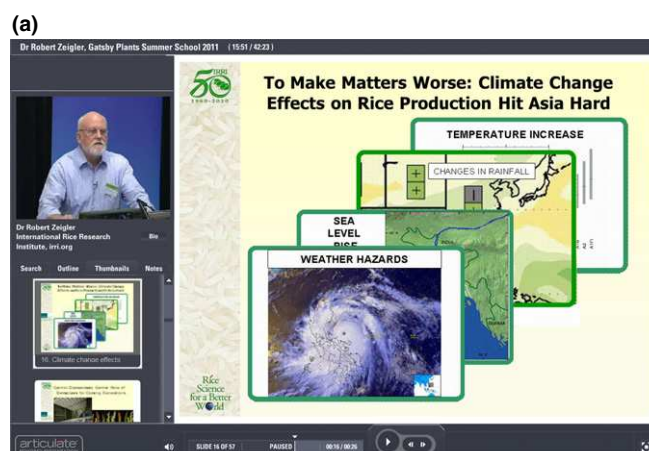

Fig. 2 'Live' vs 'online' student viewing experience of research lectures. (a) A screenshot of an online research lecture on the 'Importance of rice science and world food security' by Dr Robert Zeigler, Director General of the International Rice Research Institute, IRRI, Philippines. This, and other research lectures delivered by leading plant scientists and pitched at a level to engage undergraduates, were filmed at the Gatsby Plant Science Summer Schools. Each lecture is edited for interactive online delivery to show the speaker and their slides and has the capacity to select or search any part of a lecture using slide thumbnails or search box. All lectures may be viewed by registering with the Plant Science TREE at www.tree.leeds.ac.uk. (b) Comparison between 'live' and 'online' student viewing experiences of three pooled lectures delivered by Prof. Andrew Millar, Prof. James Barber, Prof. Ottoline Leyser. The lectures were viewed 'live' by students at the Gatsby Plant Science Summer School (235 responses) and were viewed 'online' by students from the University of Liverpool and University of Leeds (29 responses), who had not attended a Summer School. Students were asked to rate the lectures through an online survey. Blue bars, responses from those students who had watched the research lectures live; red bars, responses from students who had watched the lectures online.

lecture live at the summer school and so the two groups of students were surveyed separately (Supporting Information Table S1). Interestingly, when undergraduate students watched an online lecture at university, 86% rated it good or very good compared with 90% who watched it live (Fig. 2b), indicating that students respond very well to viewing research lectures online.

Student comments in favour of the resource included: the quality of the lecture and its engaging delivery; the flexibility to watch the lecture in their own time and pause and replay so as to allow time to take notes, reflect, or read and learn at their own pace; the unique interactive format, allowing the viewer to jump to any slide using a slide thumbnail or search facility and watch the corresponding lecture clip (Fig. 2a) and the fact that they could see the speaker on video rather than audio only, as in a podcast. Students disliked the fact that there was no interaction with the speaker and that they were unable to ask questions; they found it more time consuming than attending a lecture and sometimes experienced limitations due to their home internet speed.

Student responses to specific statements are shown quantitatively in Fig. 3. Students were unanimous that viewing an online research lecture is a good way of learning about a subject (Q4). Of 37

responses, 92% were of the opinion that the online research lectures were valuable in helping them gain an understanding of their lecture course (Q1). Eighty-six percent said that the online lectures were valuable in helping them gain an understanding of the subject (Q3) and 54% said it helped improve their course work (Q2). These data suggest that the online research lectures are an effective learning tool.

More remarkably, 62% of this sample of 37 students reported that viewing a single online lecture was sufficient to make plant science more interesting, and for 68% of the sample it was sufficient to make research more interesting (Fig. 4). All the students thought it was valuable for the lecture to be delivered by a research leader in the field and who conducted the research. Seventy-three percent of students stated that the lectures introduced them to new ideas about plant science and 84% of students also stated that the online lecture improved their understanding of how research is carried out. All students reported that they would like to see more plant science online research lectures and close to half of students wanted to see these even if they were not directly related to their course work. Furthermore *c.* 90% of students stated that they would be interested in attending a research lecture, having seen the online research lecture.
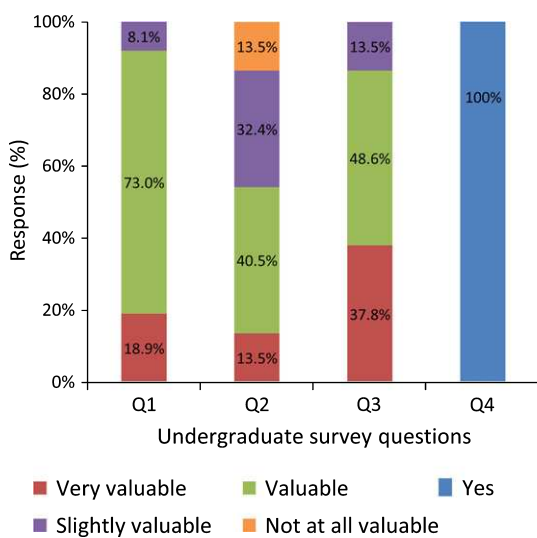

Fig. 3 Online research lectures as a learning tool. The value placed on online research lectures by undergraduates as a means to aid learning (*n* = 37). Five hundred and forty-nine undergraduate students from four UK Universities were directed to one or more of six online research lectures by their university lecturer as part of their course and then asked to fill in an online survey. Each academic directed their students to different online lectures as further information for diverse bioscience topics ranging from circadian clocks to biotechnology to photosynthesis. The graph represents the responses (*n* = 37) to the following questions:
  Q1: How valuable was the online lecture in helping you understand the lecture course?
  Q2: How valuable was the online lecture in helping you improve your course work?
  Q3: How valuable was the online lecture in helping you gain an understanding of the subject? Responses are shown from bottom: red, very valuable; green, valuable; purple, slightly valuable; orange, not at all valuable.
  Q4: Do you think viewing online research lectures are a good way of learning about a subject? Responses are shown as follows: blue, yes.
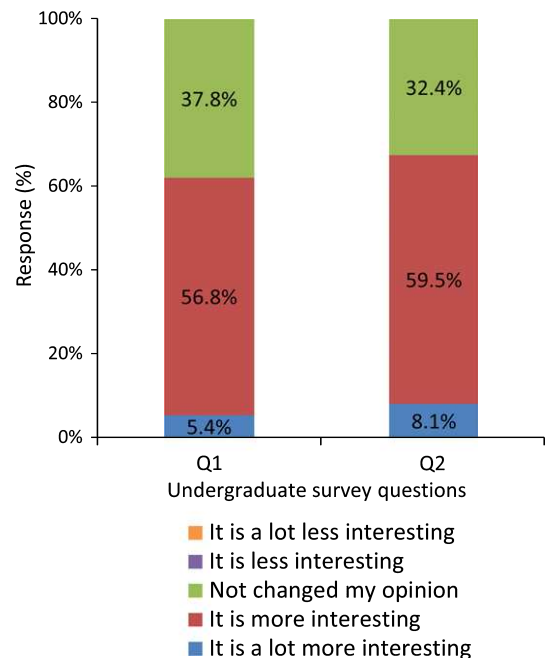

Fig. 4 Engaging students in plant science and in research. Self-reported influence of watching a single online research lecture in changing undergraduate student attitudes to plant science and research (*n* = 37). Five hundred and forty-nine undergraduate students from four UK Universities were directed to one or more of six online research lectures by their university lecturer as part of their course and then asked to fill in an online survey. Each academic directed their students to different online lectures as further information for diverse bioscience topics ranging from circadian clocks to biotechnology to photosynthesis. The graph represents the responses to the following questions:
  Q1: Has the online lecture changed your opinion of how interesting plant science is?
  Q2: Has the online lecture changed your opinion of how interesting research can be? Responses are shown from bottom: blue, it is a lot more interesting; red, it is more interesting; green, not changed my opinion.
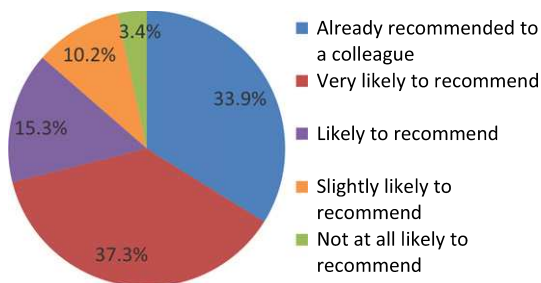
Fig. 5 The degree to which the Plant Science TREE is recommended by registered users. The chart shows the response to the question: How likely are you to recommend the Plant Science TREE to colleagues? Data are from an online survey sent out to all registered users (*n* = 59). Responses are shown clockwise: blue, already recommended the TREE to a colleague; red, very likely to recommend; purple, likely to recommend; orange, slightly likely to recommend; green, not at all likely to recommend.

Engaging the community

A good measurable indicator of a resource's impact is the extent to which it is recommended (Jisc, 2012). The fact that the TREE is highly recommended is supported by our registration data where 23% of a sample of 590 registered users, who provided information on where they had heard of the TREE, stated that it had been recommended to them by a colleague (20%) or their lecturer (3%). Furthermore, 87% of the 59 users, who responded to the TREE user survey had either already recommended it to a colleague (34%) or were likely to do so (53%; Fig. 5). Recommendations were highest amongst educators of which 44% of a sample of 27 had already recommended the TREE to colleagues and a further 48% were likely to do so. One academic commented 'I think the TREE is a fantastic resource that provides a trusted source of good, current and relevant plant science research in varied ways, particularly suited to the academic teacher/student audience. The research lectures available are a real gem and do a great job in improving the status of a career in plant science'.

Of the 37 undergraduate students, who responded to the online student survey, 97% stated that they would recommend the online research lecture they had viewed to another student.

The Plant News is also highly recommended with 81% of 54 registered users, who responded to this question on the TREE user survey, stating that they had already recommended the Plant News to colleagues (20%) or were likely to recommend it.

The newly introduced upload facility provides further opportunity to engage the community and extend the impact of this resource.

Discussion

Our data show how web technologies can be used by a community of academics to engage undergraduate students with plant science. We have offered a sense of ownership of this resource to the UK research community, involving them in its creation and generating an easy to use web-site that is already being used and recommended world-wide by educators and learners. We have furthermore established the facility to upload new content so that the resource can be kept up to date.

The TREE attracts an audience of educators, learners and researchers from over 320 research and educational institutes world-wide. Unique visitor count is often considered the most important usage indicator of a web resource and at 1600 unique visitors per month, the TREE performed well in comparison with other sites containing higher education educational resources for example Jisc funded projects such as HumBox – digital humanities resources; (1230 unique visitors per month); Siobhan Davies Dance Archive project (816 unique visitors per month); SPHERE (266 unique visitors per month) (Jisc, 2013), but not unexpectedly, received fewer visits than large sites encompassing educational resources for a wide range of disciplines, such as the University of Leeds iTunes U channel (3982 total visits per month since its launch in October 2013) (University of Leeds Digital Learning Team, pers. comm.). Furthermore, accounting for 75% of unique visitors, the Plant News was key in drawing users to the site.

The TREE was developed for use by the higher education sector and has engaged this target audience, with one-third of registered users being academics and another third, undergraduates. It should be noted that the TREE was developed to provide resources for educators only, based on the principle that educators would have a wider reach and greater impact than if students used these resources for self-learning. However, it became clear that some resources, especially the online research lectures, offered immediate benefit to learners and access to these areas were subsequently opened up to registered students.

The impact of the TREE on teaching practices

Our evidence from both educators and students shows that embedding online research materials from the TREE in undergraduate teaching enhances the learning experience of students. All users appreciated the high quality of the TREE content and the browsing structure was well received, with many stating that it was easy to locate topics, find related resources and some liked the fact that it allowed for serendipitous finds. Various educators stated that having a single quality trusted site had saved them time in looking for resources in alternative sources. As the availability of online educational resources continues to grow, the emphasis will shift to collation and organization – the TREE is well-positioned to fulfil this role for plant science and, if scaled, to other fields. The fact that the vast majority of survey respondents had either already recommended the TREE to colleagues or were likely to do so (Fig. 5) provides further evidence to support the view that the TREE has been adopted by the plant science community.

Encouraging academics to consider embedding open educational resources within their learning and teaching practices has been noted elsewhere to be a significant challenge (Morris, 2013). Despite significant investment in the production of digital resources, use within higher education is often disappointing and digital libraries often face an uphill struggle to gain visibility among educators and students (Mervis, 2009). Our results are particularly encouraging and we believe that engaging the higher education plant science community in its development has provided a sense of ownership that was essential for creating a tried and trusted

repository of peer selected content with wide appeal amongst academics.

The impact of the online research lectures on student learning and subject engagement

The most popular type of resource within the TREE is the Gatsby Plant Science Summer School online research lectures given by research leaders who are passionate about their subject and who have delivered the lecture at a level to enthuse and engage undergraduates (Fig. 2). Our case study shows that, when placed within the context of a lecture course and offered as supporting material, the online research lectures are an effective learning tool that helps students understand their lecture course, their subject and improve their course work. Importantly, students are unanimously of the opinion that viewing an online research lecture is a good way of learning about a subject, suggesting that complex concepts such as energy, metabolism and circadian clocks can be successfully conveyed through plant science research examples.

Interestingly, our results show that undergraduates respond almost as positively to an online lecture as watching it live (Fig. 2b). Studies which have compared 'face-to-face only' delivery of lectures with 'webcast/podcast only' delivery support our findings and have reported either no significant difference in the academic achievement of students (O'Bannon *et al.*, 2011) or have even reported increases in grades amongst students who listened to podcast lectures only compared with lecture attendance only (McKinney *et al.*, 2009). Furthermore, online lectures offer the advantage of allowing the student to revisit parts of the lecture to improve understanding, but do not allow the opportunity to interact with the lecturer and ask questions.

A remarkable finding was that viewing a single online research lecture was sufficient to make plant science and research more interesting for a majority of students (Fig. 4). Our results also indicate that students want to see more online research lectures even if they are not directly related to their course work. The online research lectures engaged students from a wide range of courses and abilities and show that, when appropriately engaged, many students can be interested in subjects that do not form part of their core curriculum, stimulating their intellectual curiosity. Furthermore, students value the style of presentation and the opportunity to see the speaker, which is not present in all sources of online lectures (e.g. Henry Stewart Talks). Interestingly, 97% would recommend the online lectures to other students, which suggests an excellent potential for peer-to-peer dissemination of this valuable resource.

An important attribute of the TREE resources is their potential for global audience reach. Two hundred and forty students watched 17 'live' summer school lectures between 2010 and 2012 at the Gatsby Plant Science Summer Schools that accommodate 80 students each year (Levesley *et al.*, 2012). After editing for online delivery these lectures were viewed 3735 times online through the TREE between August 2010 and May 2013 by a wide audience, representing a 15-fold larger 'online' audience compared with 'live' audience.

Harry Kroto, the chemistry Nobel Laureate and founder of the educational repository GEOSET, argues that the best (educational) materials often come from 'people who are passionate about what they are doing and want to share it' (GEOSET; Mervis, 2009). This is our experience too and is evidenced by the important role played by the research lectures in engaging students in plant science at the Gatsby Plant Science Summer School (Levesley *et al.*, 2012) and by this study, where we have shown that this informative and inspirational element of the summer school can be conveyed to a wider student audience through the use of web technologies.

Other studies also support the use of technology to enhance student education. For example, the combined use of podcasts and mobile formative assessments, led to statistically significant increases in grades (Morris, 2010) and a study where students accessed the content online and came to class ready to make best use of their time with the instructor led to accelerated learning (Lovett *et al.*, 2008). The examples presented here offer a range of possibilities for educators to use the TREE resources in their teaching which could free up time to assess understanding of the topic or to cover related topics.

These results have implications and open up possibilities of using advances in technology to engage students through quality online research talks. Our results show that students place a high value on the opportunity to watch research leaders talking about their research. For example, through the TREE, students currently have the opportunity to watch talks by Prof. Peter Beyer, co-inventor of Golden Rice; Prof. Julian Hibberd who talks about the landmark research on engineering C_4 photosynthesis into rice; Prof. Jim Barber on building an artificial leaf to efficiently capture and use solar energy; Prof. Sir David Baulcombe on science and the sustainable intensification of global agriculture, to name but a few. Through these and other research talks, undergraduates are supported to realize not only the contested uncertain nature of knowledge, but also the importance and the fascination of pursuing that knowledge.

In conclusion, we present a web resource that is effective at engaging both educators and learners with plant science. As such it is an educational tool for wide and varied application and may also be a useful template for other disciplines.

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Supporting Information

Additional supporting information may be found in the online version of this article.

Table S1 Methods employed to gather data for the Plant Science TREE impact study

Table S2 Further information from a case study to assess the impact of online research lectures as a learning tool and as a means to engage students into plant science or research in general

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