# Modelling Ecosystem Structure and Energy Flow in a First Year Environmental Biology Practical: Not a Complete Waste of Energy

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**Keywords:** ecosystems, energy flow, field work, quantitative skills, simulation

International Journal of Innovation in Science and Mathematics Education, *20*(3), 30-37, 2012.

## Abstract

The modelling of energy flow through ecosystems is conceptually difficult, and has been shown to be complicated to teach, at both the secondary and tertiary levels. Endeavours to integrate such modelling into a first year environmental biology curriculum are thus likely to pose considerable challenges. This paper reports on efforts to quantitatively model energy flow through a simplified, paper-based ecosystem in a first year environmental biology unit. In addition to curriculum-related objectives, the broader aims of the initiative were to enable students to apply concepts and processes introduced in lectures and readings, enhance learning through collaboration and discussion about energy flow and ecosystem trophic structure, and develop student skills in oral or visual communication. Although some aspects of the project, such as collaborative learning and class presentations, were moderately successful, student deficiencies in quantitative skills, together with the simplistic nature of the 'paper ecosystem' meant that numerical analyses were complex and subjectively made. One misconception was that a complex ecosystem, conveniently divided into trophic categories, could be simplified in terms of energy flow from source to sink. Following revision and the inclusion of more structured guidelines, the project was reintroduced to the biology program. The revised project was more successful in terms of student consistency and accuracy in modelling energy flow and also with regard to their overall satisfaction with the project. Nevertheless, after considerable deliberation, it was decided that a hands-on, field-based project would provide a more true-to-life experience in the context of the first year environmental biology curriculum.

## Background and rationale

The study of ecosystem structure, together with investigations of the interactions among organisms and energy flow within ecosystems, are common elements of general biology curricula offered in Australian science degree programs, in particular those with a focus on environmental science. At one scale, an understanding of ecosystem structure together with its various food chains and resultant overall food web might be considered conceptually simple. However, the modelling of energy flow in an ecosystem, particularly in quantitative terms, is more conceptually challenging, and therefore more difficult to teach, as has been found at both secondary (Eilam, 2012; Lin & Hu, 2010) and tertiary (Doberski, 1998; Hartley, Anderson, Abraham, D'Avanzo, Arnett, Dickman, Griscom, Maskiewicz, Picone, Schramm, & Wilke, 2009) levels. Endeavours to integrate such modelling into a first year practical teaching program face considerable challenges.

The need for, and importance of, quantitative skills in undergraduate science degrees has long been recognised by educators (Gross, 2004). In biology in particular there have been increasing calls for greater emphasis on enhancement of such skills (Goldstein & Flynn, 2011; National Research Council, 2009). The inclusion of quantitative analysis as a component of biology curricula has been shown to strengthen the ability of students to make connections between statistical concepts and their use in analysing biological data (Metz, 2008). Further, in a study of the academic achievement of college science students in the United States, Sadler and Tai (2007) found that one of the two pillars correlated with academic success was a more advanced study of mathematics in high school. Thus, the development and introduction of a practical exercise that reinforces and applies elements of the underlying curriculum, and additionally sets out to refine, enhance and apply student skills in the application of mathematical concepts and skills, is based on sound pedagogical principles.

This paper reports on efforts to quantitatively model energy flow through a simplified, paper-based practical based on a 'model' ecosystem. The exercise was adapted from Aston (1988), who originally devised the exercise primarily for senior secondary biology students. This paper will also report on subsequent modification and enhancements to the exercise to make it more intuitive, relevant and engaging for students interested in broader environmental biology courses and concepts.

## Development and integration of the practical

The rationale for using a paper- rather than field-based exercise was based on a number of factors, including (a) the nature of the curriculum, which includes aspects of populations and communities, followed by the study of ecosystem functioning, biogeochemical cycling, and trophic structure; (b) the nature of the cohort, which comprises a broad diversity of students with different levels of prior learning and capability, and (c) the comparatively large enrolment (approx. 200 at the time), and resultant logistic difficulties and high costs associated with taking large numbers of first year students out into the field.

The aims of the exercise were:

(i) consider the relationship between the structure of an ecosystem and the flow of energy through it;
(ii) appreciate that complex ecosystems can often be simplified and conveniently divided up into trophic categories and the flow of energy traced from source to sink;
(iii) experience and understand some of the procedures associated with examining and quantifying patterns of energy flow through an ecosystem;
(iv) identify some of the main variables that would need to be measured in a real ecosystem study on energy flow;
(v) and consider some of the problems associated with quantifying ecological variables and procedures adopted.

Other aims associated with the practical were to enable students to apply concepts and processes introduced in lectures and readings; enhance learning through collaboration and discussion about energy flow and ecosystem trophic structure, and; develop oral or visual communication skills.

Each group of students was provided with a large scale (A3-sized) image of the model paper ecosystem (Figure 1), a set of instructions for working through the exercise, a worksheet and a transparent grid of 1 $mm^2$ graph paper. The paper-based exercise was divided into four sections for base calculations; estimation of the 'standing crop'; determination of the amount of light falling on the plant; calculation of the patterns of energy assimilation and loss over a 24 hour period; and estimates of the amount of respiration occurring at each trophic level (Figure 2). Different groups of students were each assigned one of the above four tasks.

Students then used their derived values to calculate the factors of ecosystem functioning, such as assimilation efficiency, maintenance costs and finally an overall ecosystem parameter, known as Lindeman's ratio, which quantifies the loss of energy at each linkage between successive levels of the ecosystem under investigation.

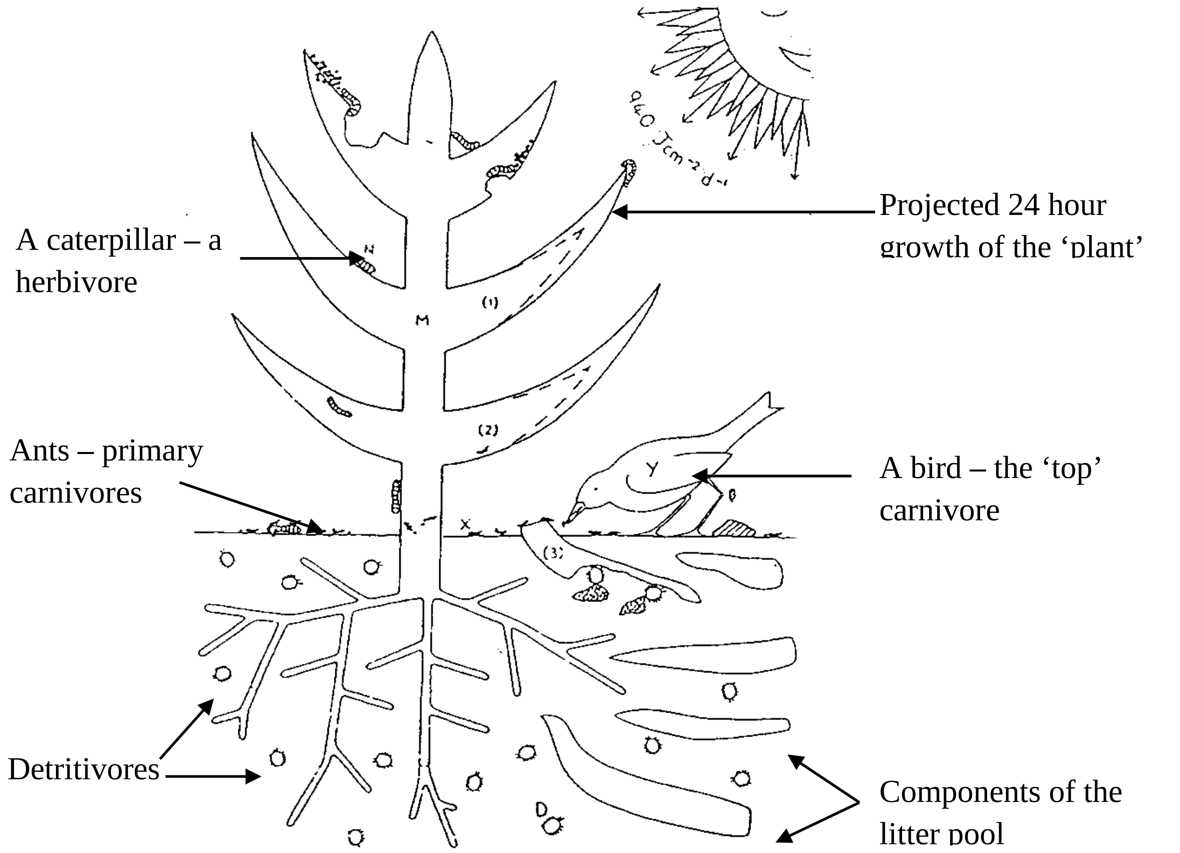


Figure 1: The simple paper-based ecosystem used as a basis for calculating standing crop and modelling energy flow between trophic levels (adapted from Aston, 1988).

This exercise makes some basic assumptions, which influenced students' perceptions of it and thus complicated to varying degree their calculations of parameter values. The assumptions were: (i) that light illuminates only one side of the above-ground parts of the two-dimensional plant; (ii) that the above-ground plant parts grow by the same proportion over the 24 hour period; (iii) that the area of the paper is proportional to the mass of the trophic level; and (iv) that 'growth' in the ants and bird were both negligible during the 24 hour period. A high proportion of students found one or more of these assumptions to be either confusing or at worst, counter-intuitive.

In order to streamline the exercise, students worked in groups of four. This also served to enhance peer discussions and interchange, and thus helped to cater for the considerable diversity among students with regard to prior knowledge, understanding and ability to apply and synthesize information. Having students work together collaboratively, to share, construct and refine their knowledge aligns with theories of social constructivism (Vygotsky, 1978). This element was taken one step further in this exercise, with students discussing and deciding on estimates and calculations, developing an overall flow chart of energy flow between trophic levels and then delivering a presentation to their peers, thus further developing skills in information and communication technologies and public speaking.

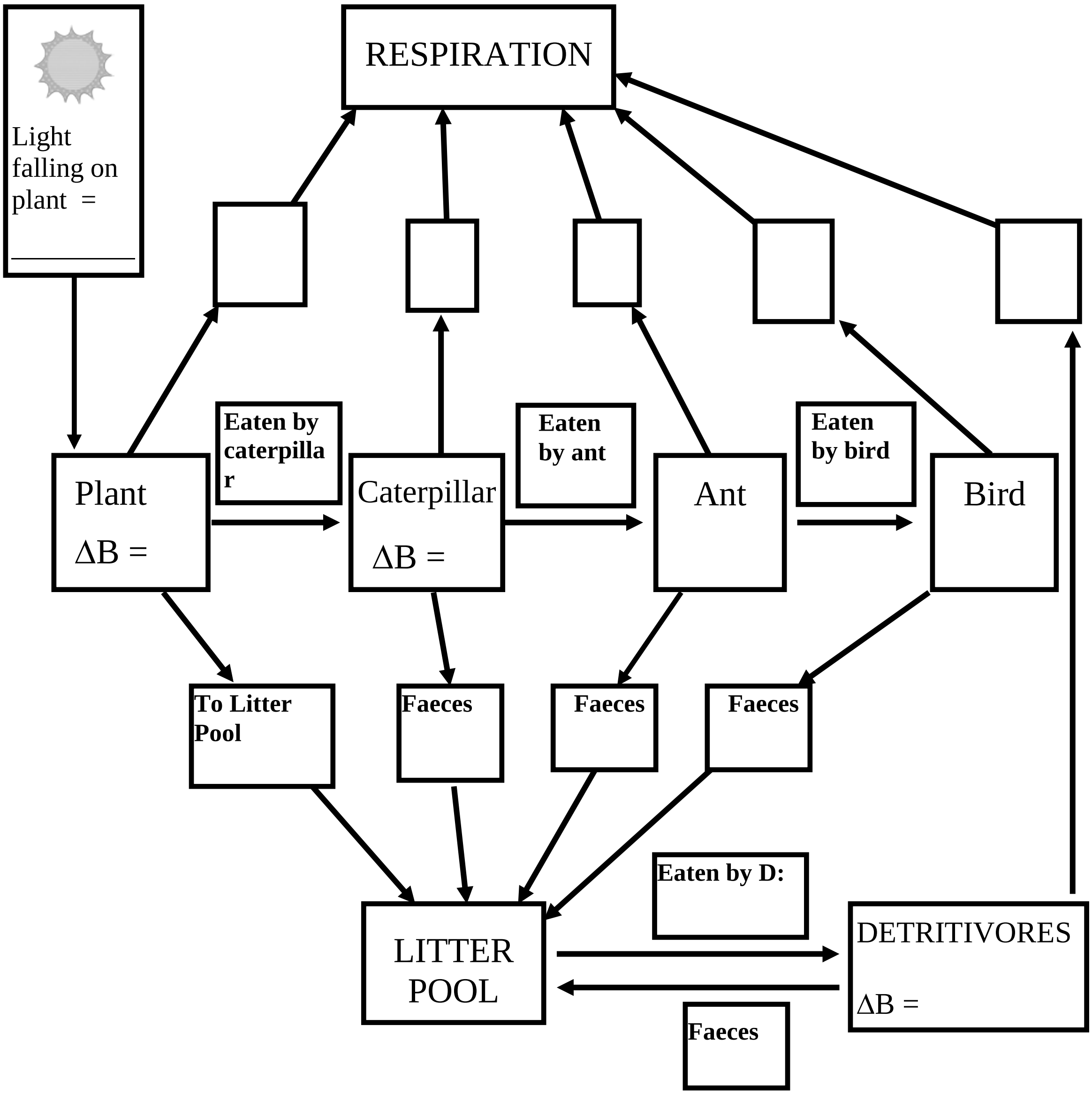


**Figure 2: Proposed energy flow diagram for the model ecosystem (values in J d$^{-1}$) (adapted from Aston 1988).**

After considerable discussion, revision and provision of more structured guidelines, the project was reintroduced to the first year program. The unit coordinator had observed that in the main, apart from lectures related directly to ecosystem structure and food webs, students were attending this practical without completing any related preparation. One modification thus required students to read and submit answers to three preliminary questions before commencing the practical.

## Key lessons learnt

The benefits of introducing this paper-based exercise were primarily associated with the enhanced communication skills students gained through the peer-led collaborative discussions and group presentations of final energy flow diagrams. To some extent, these outcomes reinforce the very broad acceptance of the effectiveness of peer-led active learning-type pedagogies. Another positive outcome was that student calculations of standing biomass and energy flow calculations were *largely* consistent with models presented in lectures about ecosystem structure, energy flow and food webs, and should thus have deepened student understanding of such concepts.

There were a number of difficulties in administering this paper-based exercise as an effective learning activity. Firstly, the simplistic nature of the 'ecosystem' created a degree of confusion among students and debate within and between groups, resulting in a considerable range of values being obtained for the same parameter among different groups. In spite of the guidance offered by teaching assistants, students considered the numerical analyses to be too complex and subjective to derive accurate, consistent and meaningful results.

An underlying hypothesis of this practical was that a complex ecosystem, conveniently divided into trophic categories, is able to be simplified quantitatively in terms of energy flow from source (the sun) to sink (the consumers). However, a high proportion of students struggled with what were considered relatively simple mathematical operations, such as calculation of means and ratios. Further, many students found it difficult to apply the concepts and calculations to derive Lindeman's ratio, and thus the biological implications of this part of the practical were at best poorly made, and in a worst case scenario, only served to confuse students even more about the nature of energy flow and trophic efficiency. However, as stated above, the considerable range of values obtained by different groups for various components of the energy flow model suggests that either the model was too complex, or that many students were not sufficiently skilled to carry out what were considered to be relatively basic quantitative skills. The results indicate that this deficiency in quantitative skills was not ameliorated by group-based interactions and discussions.

The revised and reintroduced energy-flow practical was somewhat more successful in terms of the consistency of student results, the accuracy of modelling energy flow and also with regard to their overall satisfaction with the project. However, several underlying conceptual problems remained with the practical. These included the complexity associated with making meaningful connections among the various 'strands' of the paper ecosystem, such as standing crop, the patterns of energy assimilation and loss over the time period, the shortness of the time period over which these estimates were made, and the parameters of ecosystem functioning. The major issue, at least from the student perspective, was an inherent difficulty to model biomass and thus standing energy in terms of a two dimensional area (the paper), rather than more conceptually tangible measures such as dry weight, or rates of photosynthesis and/or respiration, together with associated parameters such as growth or population increase.

There are several key lessons to be taken from this attempt to integrate a paper-based exercises investigating the flow of energy through a simplified ecosystem. Firstly, a high proportion of students' were unable to undertake even relatively simple mathematical operations, including the calculation of ratios and growth parameters incorporating units. This reinforces a growing concern among educators of a widespread deficiency in the quantitative skills attributes of students entering science and science-related degree programs. This may be in part due to an apparent lack of connection in many biology courses between the role and importance of mathematical analysis to describe biological data, which has often been, as Colon-Berlingeri and Burrowes (2011) point out, an essential factor in many significant scientific discoveries. Regardless of causality, there remains a genuine need for science undergraduates to have a more thorough grounding in quantitative skills, perhaps prior to commencing their studies, and which may then be scaffolded throughout their degree. Echoing the situation in US colleges and Universities (Marsteller, 2010), deficiencies in the quantitative skills of students entering Australian science degrees is recognised as a serious issue (Brown, 2009) and further, is an impediment to the broader application of knowledge in the sciences, which is a characteristic of higher order learning by students (Goldstein & Flynn 2011). Nationally, attempts to address this issue are being made through a number of initiatives, including at the tertiary level through the ALTC funded 'Quantitative Skills in Science' project. In the US, greater traction appears to have been gained around this issue, with national reports, together with collaborations and initiatives, occurring at each level and across the secondary-tertiary divide (see Labov, Reid & Yamamoto, 2010 for examples). These initiatives also include funded liaisons between biology and mathematics departments, to provide greater integration of mathematical concepts into biology subjects, scaffolded by relevant mathematics and data analysis interventions and skills development programs.

The second lesson learnt from this exercise is that learning and skills outcomes of laboratory or field based projects, particularly those with an ecological 'flavour', are likely to be strongly aligned with its *contextual* strength and realism. This means that a practical such as this one, incorporating elements of ecosystem structure and the energy flow across trophic levels, may be more likely to achieve its aims through a hands-on, field-based project running over a number of weeks and incorporating actual measurements of various physiological and species parameters. This suggestion is supported by a range of studies, including that of Rahman and Spafford (2009), who found that biology students perceive field trips as necessary, and also see them as positive learning experiences for contexts such as enhancing understanding of subject material and development of graduate attributes. Further, field trips incorporating aspects of inquiry, hypothesis formation and experimental design add considerably to student learning by providing a very strong nexus between teaching and research (Gamarra, Ironside, de Vere, Allainguillaume, & Wilkinson, 2010).

The final lesson learnt from this experience has been to recognise the importance of structuring ecology- and ecosystem-related practicals so they are inquiry-based (i.e. starting with a question), engaging, group-driven, and also where possible, enjoyable. In the sciences, learning modalities outside the lecture theatre or laboratory, in informal settings such as on field trips, which incorporate elements of social interaction, fun and enjoyment have increasingly become casualties of very crowded, knowledge-based curricula (Scott , Goulder, Wheeler, Scott, Tobin, & Marshman, 2012). Nevertheless, having fun and sharing the enjoyment with other students have been shown to be important components in the learning 'mix' (Griffen, 2008), and their potential value in tertiary settings should not therefore be underestimated.

## Modifications that generated a more educationally valuable outcome

Given these concerns and after considerable deliberation, the 1$^{st}$ year biology coordinating group decided that a hands-on, field-based project, involving sampling, identification and food chain construction of an actual freshwater ecosystem would provide a more engaging and true-to-life experience in the context of the environmental biology curriculum. The field site selected for study was the Jock Marshal Reserve, a small remnant (approx. 3 Ha) of semi-natural vegetation and wetland located in the north-east corner of the Monash University Clayton campus. The project again involved students working in groups of four. Over the course of several weeks, each group sampled the fauna from different habitats in the wetland, constructed food chains and an overall food web, estimated relative abundances of the various feeding groups and from this, indices of biotic diversity. Alongside this, students also explored comparative rates of breakdown of different leaf types in three wetland habitats, and together with measures of water quality (i.e. pH, conductivity, turbidity, and phosphate levels), investigated possible connections among leaf type, habitat type and faunal assemblages.

The decision to conduct a field-based exercise for investigating ecosystem structure has been validated by a range of research studies that show the greater value, in terms of both student perceptions and demonstrated student knowledge, of actual versus simulated or virtual field trips (Scott et al., 2012; Spicer & Stratford 2001). However, this is not to deny the potential value in students undertaking a simulated or paper-based exercise *as a prelude to or in planning for* an actual field trip. Further, although the pedagogical value of simulated or virtual field trips in biology and ecology will undoubtedly improve with technological advancements in software design and sophistication, it is unlikely that paper-based scenarios can ever replace real-time student-active field-based exercises, variously integrating elements such as experimental design, inquiry and hypothesis formation, observation, and the gathering, presentation and interpretation of data.

Based on anecdotal feedback from students, together with comments in subsequent unit evaluations, this more hands-on practical, situated in a semi-natural environment, has been a resounding success and provides a valuable springboard for upper undergraduate studies such as zoology, botany, ecology and conservation biology. In subsequent evaluations of this unit over the years 2009-2011, students have very strongly endorsed the use of the field site for hands-on field-based projects such as the revised ecosystem structure and energy biomass practical. Student comments in response to the question, "What were the *best* aspects of the unit?", included the following:

> *"Doing field work in the Jock Marshal Reserve instead of being stuck in a lab"*
> *"Hands on work in the Jock Marshal Reserve".*
> *"I thought it was great to get outside to do the practicals."*
> *"It was very hands on which made it quite interesting. I enjoyed having the prac classes in the Jock Marshal Reserve."*
> *"The practical classes at the Jock Marshal Reserve. Was great being more outdoors and more hands on, and being able to view live organisms."*
> *"The practical sessions were the best. They were enjoyable, challenging, active, interesting and engaging."*

Perhaps the essential value of attempting to integrate this paper-based exercise into a first year environmental biology subject is that it mirrors, to some extent, the fundamental nature of scientific endeavour of *trial and error*. In fact, it might be argued that many scientists spend a greater amount of time trying to discover why certain experiments either do not work or yield the predicted results, rather than carrying out experiments and generating results that confirm their predications or actually generate the 'aha' or 'yahoo' moments. Although students who undertook the early incarnations of this practical may not agree, both retrospection and reflection are essential ingredients of science, in terms of both nature of scientific discovery and the pedagogy of science. It also reinforces the value and importance of 'having a go', of implementing learning modalities and initiatives that may not initially bear the desired pedagogical 'fruit', but which are never a 'complete waste of energy'.

## Acknowledgements

The author acknowledges the input of academic colleagues, including a number of teaching associates, in their efforts to make this paper-based a more valid and effective learning experience. I would like to further acknowledge the various cohorts of students who engaged with previous incarnations of the practical and who provided considerable feedback on both positive and negative aspects of the exercise.

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