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Setting site specific Critical Loads: an approach using Endorsement Theory and Dempster-Shafer.

RICHARD A WADSWORTH* & JANE R HALL

*corresponding author.

CEH Monks Wood, Abbots Ripton, Huntingdon, Cambridgeshire, PE28 2LS, UK.

E-mail rawad@ceh.ac.uk

Tel: +44(0) 1487 772433

Fax: +44(0) 1487 773467

Abstract

There is an increasing demand from conservation agencies for site-specific critical loads (CL); unfortunately, there is often very little specific information on a site to determine the important parameters needed to calculate the CL or on the spatial location of the "designated feature" in a site. Determining the most appropriate CL therefore involoves using expert judegement to make decisions with incomplete and uncertain information. Endorsement Theory (Cohen 1985) and Dempster-Shafer statistics (Dempster 1967, Shafer 1976) are, respectively, a decision-theoretic and a statistical technique for reasoning under those conditions (uncertainty and incompletness). A key reason for applying these techniques is that they make expert opinion explicit and available for scrutiny. Both techniques have been applied to the problem of setting an appropriate site specific CL, using heathland sites as a case study. Inital findings are encouraging; the uncertainty in expert judgement is made explict, the end results are intuitively reasonable and the methodology apparently acceptable to decision makers.

Keywords: Endorsement Theory, Dempster-Shafer, Uncertainty, site specific critical loads.

1. Introduction.

A Critical Load (CL) is “a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge”. The concept arose in the 1980’s as a response to concerns over transboundary (international) air pollution and particularly “acid rain”. Because of these concerns a tool or methodology was required to help in assessing the effect of alternative policy options to control the emission of pollutants, and their subsequent dispersal, deposition and impact; CL were therefore designed to work at the broad level of international agreements and protocols (see http://critloads.ceh.ac.uk for more details). They are most commonly calculated for acidity (caused by sulphur and nitrogen oxides) and eutrophication (nitrogen); CL are calculated for soils and freshwaters. Over the last two decades a number of refinements to the methodology and data have been made, however, across all of Europe there are only a handful of locations where all the information required to calculate the soil acidity CL has been measured. Recently there has been an increasing demand from conservation agencies for site-specific CL, particularly for sites designated for biological conservation (Special Areas of Conservation, Special Protection Areas, etc.). Using national data to generate site specific values can give misleading results; generally the location of the boundaries of the site are unavailable and the site is reduced to a “point”, national data use of the dominant soil and land cover in a one kilometre square and these may be wrong or inappropriate for the site. In a national estimate with many hundreds of sites these errors will cancel each other out and a robust estimate can be made (of the national situation), but for someone familiar with a particular site any discrepancies will be disconcerting.

There is usually only a limited amount of relevant site-specific information and what information that is available often requires interpretation. One piece of information that is always available from the Conservation Agencies is the vegetation type, which is always described within well defined and detailed classification systems. We sought an analysis method that would allow us to exploit whatever local information was available whilst making the uncertainty in expert opinion an explicit part of the reasoning process; Endorsement Theory (Cohen 1985) which was designed for reasoning with incomplete information meets these requirements. Confidence in the CL estimated from the site-specific information will be variable; the "best" CL value should combine both the local and national estimates. We wished to keep the uncertainty in both estimates explicit and therefore combine both strands of evidence using Dempster-Shafer (Dempster 1967, Shafer 1976) which in this context is effectively an extension of Bayesian statistics.

2. Using Endorsement Theory to set site specific Critical Loads

Endorsement Theory (ET) (Cohen 1985) is a form of reasoning with incomplete and uncertain evidence. The approach was developed in the AI (artificial intelligence) community in an attempt to develop systems that could reason in a more human manner and particularly the ability of human experts to "diagnose" situations with limited information. The approach is particularly useful for:

- Allowing inference to be made from partial knowledge.
- Making the reasoning process explicit, traceable and highly heuristic.
- Avoiding the need to translate expert knowledge into numerical values. In the case of trying to set a site specific CL we typically do not have much information on the environmental conditions in the designated site, even such crucial information as the soil series is not consistently readily available. Typically the location of the designated feature (ie, habitat or species) is unknown (or is unavailable), nor is there often information on the relationship between the designated feature and the limited number of habitats for which CL methods are available. ET is

a way of marshalling whatever local information we may be able to obtain for a site and of providing a very simple indication of the expected reliability of the information.

In the UK soils have been categorised into six acidity CL classes; five for mineral and organo-mineral soils (Loveland 1991; Hornung *et al*, 1995), and a sixth class for the peat soils for which a different methodology is used (Calver *et al* 2004). For the purpose of using ET we consider each CL class *as if* it were a separate hypothesis. We seek to determine the extent to which the available data supports each hypothesis. The procedure to produce an endorsement for a CL for a site can be summarised as;

- Determine what "designated features" exist on the site; these can be habitats or species and in general information on their exact location is unavailable.
- Assume that protecting the existing vegetation will protect the designated feature.
- Reclassify the recorded vegetation classes in terms of the National Vegetation Classification (NVC) (Rodwell 1991 *et seq*) (many sites are already described in terms of the NVC).
- Using the descriptions in the Rodwell books obtain information about the environment where the relevant NVC class(es) is typically found.
- Process the environmental information in Loveland (ibid) to produce Look-up-Tables of the "weight of evidence" than an environmental factor gives to each CL class.
- Link the environmental information from the NVC to the environmental information in Loveland (ibid) on the basis of common terms and synonyms.
- Combine the "weights of evidence" for all the environmental factors relating to an NVC class to produce an "endorsement" for each CL class.

2.1 Primary information sources

Information on the designated features and the vegetation cover of the designated sites is always obtainable from the Conservation Agencies and will not be discussed further.

The NVC (Rodwell 1991 *et seq*) is the *de-facto* standard description of natural and semi-natural vegetation communities in the UK. Each class is described over several (~10) pages of text, but, the amount of environmental information (soils, geology, topography, climate, geography, management etc.) is inconsistent; communities are also very variable in their fidelity to particular conditions. Information about each class has been extracted and stored in an MS Access database as text using Rodwell's vocabulary; examples for two heath communities are shown in Table 1.

Table 1. About here.

Loveland (ibid) uses the methodology documented in Hornung *et al* (1995) to allocate 298 soil associations in England and Wales into one of the six CL acidity classes. Information on the physical characteristics of the *dominant* soil series in each association is also provided, for example, for the Worcester association (431):

Geology: Permo-Trias red mudstone,

Mineralogy: Chlorite / carbonates,

Texture: Clayey / fine loam,

Land Use: Stock rearing / arable,

Comment: Slow drainage.

CL class: 2.0-4.0 keq ha^{-1} yr^{-1}

All soil associations are described in the national hierarchical soil classification scheme (NSRI, Soil Survey 1985); the Worcester association (431) being:

Major group: Pelosols,

Sub-group: Argillic pelosols,

Type: Typical argillic pelosol.

The data in Loveland has been summarised into seven look-up-tables (LUT); “soil association”, “major group”, “sub-group”, “type” “texture”, “geology” and “comment”, (that is excluding “mineralogy” and “land use”). In each LUT the cells in the table record the number of soil associations that share a particular attribute and have been allocated to a particular CL class. In Table 2 (an example LUT) it can be seen that there are a total of 130 soil associations in the major group “brown soils”, of which three have a CL of 0-0.2 keq ha^{-1} $year^{-1}$; 27 have a CL of 0.2-05 keq ha^{-1} $year^{-1}$; 57 a CL of 0.5-1.0 keq ha^{-1} $year^{-1}$ and so on.

Table 2 about here.

Table 2 shows that some “major groups” have a high fidelity to a particular CL class eg. “podzol”, others eg “brown soils” are much more variable and the “lithomorphic” group appears to be bi-modal (those derived from chalk and limestone versus those derived from granite and sandstone).

Expert opinion is used to decide how much “weight of evidence” should be put on each entry in the LUT; for example how much reliance should be put on the observation that 3 out of 130 soil associations in the “brown soil” group have a low CL and how much weight should be given to the observation that 20 out of 29 “podzol” group have a high CL? We contend that most people consider that 20 out of 29 provides stronger evidence than 3 out of 130; the question is how to express that belief? In a standard knowledge engineering approach numerical scales are used eg choose a number between 0 and 10. In ET the scale is expressed in words (eg weak, strong, overwhelming) and it is the responsibility of the domain expert and not the knowledge engineer to define this “scale”. We used a scale with four categories; “strong”, “moderate”, “weak” and “very weak”. Other experts may prefer other categories; in the context of land cover change Comber *et al* (2003) use; “conclusive”, “prima-facie”, “strong” and “weak”; whatever scale is chosen by the domain expert they have to be explicit. Having defined their scale the expert needs to allocate each value in the LUT into one of their categories. In this case the two cells marked “s” in Table 2 are the only ones to provide a “strong” weight.

2.2 Relating NVC soils information to soils terminology used by Loveland

The environmental information provided about each NVC classes needs to be related to the terminology used by Loveland. Sometimes there is an exact correspondence between terms used in the NVC and in Loveland and the NSRI. More often terms are similar but different, for example, “brown soil” in Loveland and “brown earth” in the NVC. In some cases there is no correspondence; for example, several NVC communities are associated with the “Borrowdale Volcanics” in the Lake District, but Loveland does not use that term. A LUT is used to relate the NVC terms to the Loveland terms, in linking the terms we are conservative and when in doubt we do not infer a connection.

2.3 Combining the Evidence to produce an Endorsement

The weights of evidence for each piece of environmental information are collated and combined to produce an overall endorsement for each CL class for the NVC class in question; in ET the categories are determined by the domain expert and are expressed in words not numbers. We use a scale with five levels of endorsement:

- "Definitive", three pieces of "strong" evidence and no conflicting evidence.
- "Confident", two pieces of "strong" evidence and no "strong" conflict.
- "Likely", at least one piece of "strong" evidence or three "moderates"
- "possible", at least one "moderate" or two "weak" pieces of evidence.
- "weak", at least one piece of evidence.

Table 1 shows the environmental data for two NVC heathland classes: H1 (*Calluna vulgaris-Festuca ovina*) and H21 (*Calluna vulgaris-Vaccinium myrtillus-Sphagnum capillifolium).* There are multiple entries for some attributes (for example H1 has three references to geology) and each of these "statements" is treated independently and given equal weight. Table 3 provides all the evidence for H1 that could be extracted.

Table 3 about here.

In this case we cannot give a "definitive" endorsement but we are "Confident" that the H1 heath should have a CL class 0.2-0.5keq $ha^{-1}yr^{-1}$. It is "Likely" that the CL is lower but there are only "weak" or "possible" endorsements for a higher CL. Repeating the process with H21 reveals a problem; H21 is associated with "fragmentary humic ranker" soils which are in the lithomorphic group. Most (20 out of 25) lithomorphic soils (the rendzinas) have a high CL (as they are derived from chalk or limestone). This leads to a strong endorsement for a high CL for H21, whereas a lower CL is more appropriate for humic ranker soils.

Of the 22 NVC Heaths none were awarded a "definitive" endorsement and only five had a "confident" attribution. Twelve Heaths are associated with rankers (lithomorphic soils) and therefore like H21 have erroneous "Likely" endorsements for a high CL. If a strict interpretation of the "precautionary principle" were adopted (ie, any evidence no matter how weak) all but two of the Heaths would be allocated to the lowest CL class.

3. Combining National and Local Estimates

ET provides an estimate of the CL for a site based on knowledge about the NVC classes; however, the CL can also be estimated from the national-scale data (http://critloads.ceh.ac.uk) based on the dominant soil in each 1km grid square. In combining the local (ET approach) and the national data we assume:

- Both strands of evidence are uncertain.
- Both strands of evidence have value.

To combine both estimates we need to either convert the national estimates into words to be compatible with ET or convert the endorsements from words to numbers, we choose the latter. Bayesian inference is concerned with the extent to which our belief in a hypothesis increases or decreases as a new piece of evidence becomes available. Dempster-Shafer (DS) (Dempster 1967, Shafer 1976) can be considered an extension of the Bayesian approach which is useful because:

- it provides an explicit representation of uncertainty and,
- weak evidence for something does not imply strong evidence for the opposite.

In DS belief and plausibility provide the upper and lower bounds of probability for a proposition; belief+uncertainty=plausibility and belief+uncertainty+disbelief=1.

3.1 Estimating uncertainty

Hall *et al* (2004) investigated the uncertainty in national estimates using a Monte Carlo approach. They generated a mean CL and variance for every one km square based on the dominant and sub-dominant soils; and showed that the assumption of a Gaussian distribution was reasonable. Given a mean and standard deviation the probability (belief) that the true value is within any particular range can be easily calculated from the cumulative probabilities of the class limits, (eg using "normdist" in Microsoft Excel). Converting the ET endorsements into numerical values is a classic knowledge engineering problem and the values in Table 4 express our expert opinion, the key methodological issue is that they are explicit, and therefore open to scrutiny and investigation into how sensitive the results are to the values selected.

Table 4 about here.

3.2 Mathematical formulation

To combine two strands of evidence we use the form of DS suggested by Tangestani & Moore (2002):

$$B_{12} = (B_1 * B_2 + B_1 * U_2 + B_2 * U_1) / \beta \qquad \text{Equation 1.}$$

$$\beta = 1 - B_1 * D_2 - B_2 * D_1 \qquad \text{Equation 2}$$

Where:

B = belief, D = disbelief & U = uncertainty;

β is a normalising factor, (to ensure that B + D + U = 1).

3.3 A worked example

Consider a site covered in H1 heath where the national data estimate a mean CL of 0.6 keq ha^{-1} $year^{-1}$, a standard deviation of 0.2 and a Gaussian distribution. Table 5 summarises the beliefs from the ET (local) and national estimates.

Table 5 about here

The strongest endorsement is for the CL class 0.2-0.5 keq ha^{-1} $year^{-1}$. From Table 5; B_1=0.75, U_1=0.2, D_1=0.05 & B_2=0.286, U_2=0.0, D_2=0.714. Applying the equations:

$$\beta = (1 - 0.75*0.714 - 0.286*0.05) = 0.450$$

$$\mathbf{B_{12}} = (0.75* 0.286 + 0.75*0.0 + 0.286*0.2) / 0.450 = \underline{\mathbf{0.604}}$$

In contrast the national data give the highest probability to the hypothesis of CL class 0.5-1.0 keq ha^{-1} $year^{-1}$; from Table 5; B_1=0.25, U_1=0.3, D_1=0.45 & B_2=0.669, U_2=0.0, D_2=0.331 Applying the equations:

$$\beta = (1 - 0.25*0.331 - 0.669*0.45) = 0.616$$

$$\mathbf{B_{12}} = (0.25* 0.669 + 0.25*0.0 + 0.669*0.30) / 0.616 = \underline{\mathbf{0.597}}$$

The beliefs in the other classes are small, for example the combined belief that the CL class is 1.0-2.0 keq ha^{-1} $year^{-1}$ is 0.013. As the hypotheses are <u>independent</u> the Beliefs <u>do not sum to one</u>. In this case the inclusion of knowledge about the vegetation community at the site will lead us to revise the CL downwards from the national estimate. If the more traditional Bayesian statistic is used (allocating all uncertainty to disbelief) the conclusion to revise the CL downwards is stronger (belief in CL class 0.2-0.5 is 0.546 and in CL class 0.5-1.0 is 0.403).

4. Conclusions

Uncertain, incomplete and contradictory information is common in all areas of environmental science. Decision makers and land managers want estimates specific to a particular designated site but they lack resources to make the required measurements. Data collected to assess national or super-national concerns will not be ideal for site specific concerns. Endorsement Theory allows incomplete information to be assessed and combined in a way that makes expert opinion explicit, traceable and transparent; for each piece of evidence we know where it came from, what "weight" it was given by the expert and how the evidence was combined to produce an endorsement. The reasons for the endorsement of any hypothesis can be clearly identified and tested against other opinions. There are a number of technical issues concerned with the use of Endorsement Theory that need further investigation, but perhaps more important is the fact that non-numeric methods like Endorsement Theory are not widely used, and the extent to which there will be cultural and organisational resistance to their use needs to be investigated. The Dempster-Shafer formalism allows the combination of uncertain information when the probability model can be assumed to be complete. Combining the two approaches provides a useful tool for combining variable and incomplete information to provide a better estimate of CL for a site.

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Tables

Table 1 Examples of Environmental Information abstracted from Rodwell (1991)		
	H1 *Calluna vulgaris* - *Festuca ovina* heath	H21 *Calluna vulgaris* - *Vaccinium myrtillus* - *Sphagnum capillifolium* heath
Soil Series	Newport + Worlington	
Soil Type	Brown sands + Non-calcareous brown sands	Fragmentary humic rankers
Soil Texture	Sandy + Sandy-skeletal	
Geology	Sandy glacio-fluvial drift + Arenaceous + Aeolian sand	
Soil pH	Acid + Low surface pH	
Soil Nutrient status	Oligotrophic + Impoverished	
Soil Processes	Signs of podzolisation	
Geological processes	Periglacial sorting + Decalcification	
Hydrology	Free to excessively drained	Free draining but always moist
Topography	Lowland + 30m (1 to 76m)	Steep sunless slopes + 289m (15 to 640m) + 34 degrees (3 to 90 degrees)
Management	Burning and grazing	Very sensitive to burning

Table 2 Count of soil associations by major soil group and critical load class.							
	Critical Load Class (ranges in keq ha^{-1} $year^{-1}$)						
Major Group	0.0-0.2	0.2-0.5	0.5-1.0	1.0-2.0	2.0-40	peat	Total
brown soil	3	27	57	3	40		130
ground-water gley	6	4	7	9	16		42
Lithomorphic	1	4			**20 (s)**		25
man-made						5	5
Peat						**11 (s)**	11
Pelosols		1	1		5		7
Podzol	20	9					29
raw gley			1				1
surface-water gley		6	9	30	3		48

Notes.
(s) Groups that provide a strong endorsement for a CL class

Table 3 Endorsement Summary for H1 *Calluna vulgaris - Festuca ovina Heath*							
LUT	Loveland Term	NVC Term (Table 1)	Critical Load Class (ranges in keq ha^{-1} $year^{-1}$)#				
			0.0-0.2	0.2-0.5	0.5-1.0	1.0-2.0	2.0-4.0
Soil name	Newport	Newport		**Strong**			
	Worlington	Worlington		**Strong**			
Soil group	Brown soil	Brown sands	V. weak	Weak	Weak	V. weak	Weak
	Brown soil	Non-calcareous brown sands	V. weak	Weak	Weak	V. weak	Weak
Soil Texture	Sand	Sandy	Mod’	Weak			V. weak
	Sand	Sandy-skeletal	Mod’	Weak			V. weak
Geology	Drift (with sandstone | peat)	Sandy glacio-fluvial drift	Weak	Weak	V. weak		V. weak
	Sand / sandstone	Arenaceous	Mod’	Weak		V. weak	
	Sand / sandstone	Aeolian sand	Mod’	Weak		V. weak	
Overall Endorsements			Likely	**Confident**	Possible	Weak	Possible

no evidence for the “peat” hypothesis which is omitted from this table.

Table 4 Conversion of Endorsement to numerical values of Belief , Uncertainty and Disbelief			
Endorsement	Belief	Uncertainty	Disbelief
“Definitive”	0.90	0.1	0.00
“Confident”	0.75	0.2	0.05
“Likely”	0.50	0.3	0.20
“Possible”	0.25	0.3	0.45
“Weak”	0.10	0.4	0.50

Table 5 Summary for the worked example							
CL Class[#]	Endorsement (Table 3)	Endorsement as numbers (Table 4)			National (with μ=0.6, σ=0.2, Gaussian distribution)		
		Bel_1	Unc_1	Dis_1	Bel_2	Unc_2	Dis_2
0.0-0.2	Likely	0.50	0.3	0.20	0.021	0.0	0.979
0.2-0.5	**Confident**	0.75	0.2	0.05	0.286	0.0	0.714
0.5-1.0	Possible	0.25	0.3	0.45	**0.669**	0.0	0.331
1.0-2.0	Weak	0.1	0.4	0.50	0.023	0.0	0.977
2.0-4.0	Possible	0.25	0.3	0.45	0.0	0.0	1.0

[#] Class ranges in keq ha^{-1} $year^{-1}$.