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A two-layer application of the MAGIC model to predict the effects of land use scenarios and reductions in deposition on acid sensitive soils in the UK

Rachel C. Helliwell,[1] Robert C. Ferrier[1] and Alan Jenkins[2]

[1] Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen, AB15 8QH, UK.
[2] Institute of Hydrology, Wallingford, Oxfordshire, OX10 8BB, UK.

Abstract

A two-layer application of the catchment-based soil and surface water acidification model, MAGIC, was applied to 21 sites in the UK Acid Waters Monitoring Network (AWMN), and the results were compared with those from a one-layer application of the model. The two-layer model represented typical soil properties more accurately by segregating the organic and mineral horizons into two separate soil compartments. Reductions in sulphur (S) emissions associated with the Second S Protocol and different forestry (land use) scenarios were modelled, and their effects on soil acidification evaluated. Soil acidification was assessed in terms of base saturation and critical loads for the molar ratio of base cations (Ca^{2+} + Mg^{2+} + K^{+}) to aluminium (Al) in soil solution. The results of the two-layer application indicate that base saturation of the organic compartment was very responsive to changes in land use and deposition compared with the mineral soil. With the two-layer model, the organic soil compartment was particularly sensitive to acid deposition, which resulted in the critical load being predicted to be exceeded at eight sites in 1997 and two sites in 2010. These results indicate that further reductions in S deposition are necessary to raise the base cation (BC):Al ratio above the threshold which is harmful to tree roots. At forested sites BC:Al ratios were generally well below the threshold designated for soil critical loads in Europe and forecasts indicate that forest replanting can adversely affect the acid status of sensitive organic soils. This illustrates the importance of proactive and responsible forestry management policies consistent with the longer term objectives of protecting and sustaining soil and water quality. Policy formulation must seek to protect the most sensitive environmental receptor, in this case organic soils. It is clear, therefore, that simply securing protection of surface waters, via the critical loads approach, may not ensure adequate protection of low base status organic soils from the effects of acidification.

Introduction

The acidification of soils and surface waters throughout Europe and North America is of considerable interest for the scientific community, national governments and international bodies. Since the advent of major industrialisation and burning of fossil fuels, surface waters in geologically-sensitive areas have become increasingly acidified in response to deposition of strong acid anions from the atmosphere, namely anthropogenic S and N (Haines, 1986). References to acidification can be traced back to the mid 19th century, Palaeoecological studies link the effects of acid deposition since then with biological impoverishment of fresh waters (Battarbee *et al.*, 1993; Battarbee and Charles, 1994). More recently, large scale commercial coniferous plantations have exacerbated the acidification of soils and streams draining sensitive areas (Nisbet *et al.*, 1995). The impact of afforestation on acidification is due to (a) base cation uptake particularly by young trees (Miller, 1981), (b) enhancement of acid input through dry deposition mechanisms (Mayer and Ulrich, 1977), and (c) reduction in water yield that concentrates pollutants in surface waters (Neal *et al.*, 1986).

The most obvious methods of controlling and reducing acidification are the elimination or reduction of acidifying compounds in the atmosphere, especially in areas most at risk. In the 1970s, the role of transboundary air pollution was identified and international co-operative programmes to reduce long-range pollution were established (e.g. Long Range Transboundary Air Pollution (LRTAP) in 1979, Helsinki Protocol in 1985, and the Large Combustion Plants Directive in 1986 (LCPD)). In June 1994, the Second S Protocol was signed by 28 European countries. The target emission reduction for the UK was set at 70% reduction by 2005 and 80% by 2010 based on 1980 levels. A more scientifically robust approach to emission reduction strategies was negotiated on the basis of a steady state

'Effects orientated' approach, founded on the critical loads concept. Several methods for the calculation of critical loads for soils and surface waters have been advanced, including steady state water chemistry, and steady state mass balance (Henriksen *et al.*, 1992). The critical load for an ecosystem is based on a 'dose-response' relationship, which can be estimated for different parts of an ecosystem. The aim is to assess the sensitivity of soil and surface water receptors and to define the environmental capacities available to absorb pollutant loads (DOE, 1994). A critical load for an ecosystem is defined as 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' (Nilsson and Grennfelt, 1988). The chemical threshold frequently used to calculate the soil critical load is 'base cation:Al molar ratio of 1' and an acid neutralising capacity (ANC) of zero for surface water. Below these thresholds, the most sensitive receptor is exposed to damage (Jenkins *et al.*, 1998). Although the soil critical load threshold was established to protect trees of conservation value, this threshold can also be used in commercial forest management. In assessing growth rate reductions and estimating the cost of forest production reduction due to acidification, the relationship between the BC:Al ratio and tree growth is important (Sverdrup *et al.*, 1993). The Second S Protocol embraces this critical loads approach and the agreed reductions were set with the purpose of protecting acid sensitive ecosystems by reducing acid deposition to pre-acidification levels (DOE, 1995).

The steady state critical loads technique, however, has been criticised for failing to include the length of time required to achieve a steady state following a change in acid deposition (Jenkins, 1995; Bull, 1991). One way to overcome such criticism lies in the development of dynamic modelling approaches. These models not only provide understanding of the processes involved in the spatial and temporal extent of acidification but, more importantly, they can be used to predict the future consequences of policy decisions. Furthermore, dynamic models represent the best technique currently available for assessing the time components of acidification, in particular sulphate (SO_4) adsorption and short-term soil buffering processes, and can also be used to assess the degree of impact in areas where the critical load continues to be exceeded. The likely future impact of changing land use management practices, such as deforestation and replanting, combined with changes in acidic deposition, can also be determined using dynamic modelling approaches.

The dynamic 'Model of Acidification of Groundwaters In Catchments' (MAGIC) has been applied to numerous catchments throughout Europe and the USA. Most of these applications aggregated soil chemical and physical parameters to one soil layer integrated to whole catchments (Cosby *et al.*, 1995; Wright *et al.*, 1994). This approach does not consider the differential sensitivity to acidification of the surface organic and underlying mineral horizons.

A two-layer application of MAGIC represents plot scale soil properties more accurately by segregating the organic and mineral horizons into two soil compartments. These compartments have distinctive physical and chemical characteristics and are distinguished by their organic matter content. The chemistry of the organic horizon is more strongly influenced by the ionic composition of precipitation and this can influence soil acidification processes. In the deeper mineral horizons, the replenishment of base cations through biogeochemical weathering can alleviate soil acidification. These two soil horizons have been represented in MAGIC by modifying the soil compartment structure in the one-layer model to produce a two-layer model (Jenkins and Cosby, 1989). To overcome spatial variability between the different soil types identified in a catchment, the organic and mineral soils are spatially weighted. The two-layer nature of upland soils also has implications for hydrological flow routing and nutrient uptake.

The results presented in this paper involve a two-layer application of MAGIC to the sites comprising the UK Acid Waters Monitoring Network (AWMN) (Patrick *et al.*, 1991).

Methods

STUDY SITES

The Acid Waters Monitoring Network was established in 1988 as part of the UK Department of the Environment monitoring programme to assess trends in surface water acidity associated with reduced acidic oxide emissions (Patrick *et al.*, 1995, Fig. 1). The network included all sensitive upland regions in the UK, across a range of acid deposition. The monitoring network included sites representing streams and lakes, afforested and non afforested catchments and a range of altitude and geological types. Conifer plantations at five sites represent the principal land use impact in the network.

DATA SOURCES AND MODEL PARAMETERISATION

Of the 22 sits in the network, 11 streams are sampled monthly, and 11 lakes are sampled quarterly. All samples are analysed for a standard suite of chemical determinands (Patrick *et al.*, 1991). The surface water chemistry indicates that the most acidified sites in the network are situated in the Galloway region of south west Scotland, the Pennines and north and central Wales. Within each region, afforestation results in increased acidification of surface waters, relative to nearby moorland catchments (Jenkins *et al.*, 1998).

The Acid Deposition Monitoring Network (ADMN) comprises a network of 32 sites across the UK where prin-

Site	Name	Grid Reference	Area (ha)	Forestry %
1	Loch Coire nan Arr	NG 808422	897	<1
2	Allt a' Mharcaidh	NH 881045	998	2
3	Allt na Coire nan Con	NM 793688	790	50
4	Lochnagar	NO 252859	92	0
5	Loch Chon	NN 421051	1470	51
6	Loch Tinker	NN 445068	112	0
7	Round Loch of Glenhead	NX 445068	95	0
8	Loch Grannoch	NX 542700	1287	70
9	Dargall Lane	NX 449786	210	0
10	Scoat Tarn	NY 159104	95	0
11	Burnmoor Tarn	NY 184043	226	0
13	Old Lodge	TQ 456294	240	5
14	Narrator Brook	SX 581685	240	0
15	Llyn Llagi	SH 649483	157	0
16	Llyn Cwm Mynach	SH 678238	152	51
17	Afon Hafren	SN 844876	358	50
18	Afon Gwy	SN 824854	210	0
19	Beaghs Burn	D 173297	273	0
20	Bencrom River	J 304245	298	0
21	Blue Lough	J 327252	42	0
22	Coneyglen Burn	H 640885	1414	5

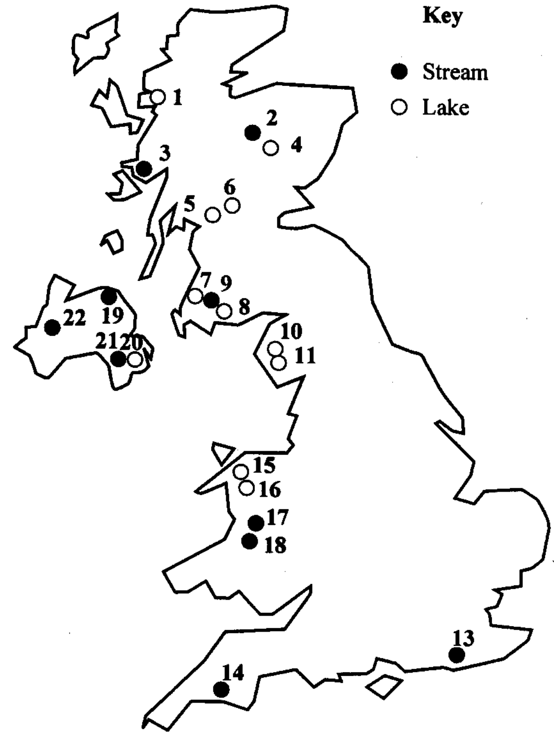


Fig. 1. *Location of the UK Acid Waters Monitoring Network (AWMN) sites*

cipal ions are measured weekly (Devenish, 1986). This is administered by AEA Technology's National Environmental Technology Centre (NETCEN). In the present study, mean wet deposition for 1988–94 was calculated for the AWMN sites (Jenkins *et al.*, 1997, 1998) from the most suitable ADMN collector (Devenish, 1986).

For the Scottish sites, soil physical and chemical parameters were selected from the Scottish Soils Database held at the Macaulay Land Use Research Institute (MLURI). From this database, soil profile descriptions are available on a 5 km^2 grid and soil chemical analyses on a 10 km^2 grid. Soil data for the English and Welsh sites were derived from previous AWMN reports, and from soil memoirs for specific sites (Lee, 1975, Rudeforth *et al.*, 1984). The soil-weighting procedure described in Jenkins *et al.* (1997) was modified to generate soil parameters necessary for a two-layer application of MAGIC, by segregation into organic and mineral horizons. Soils with >70% weight loss on ignition were classed as organic, whilst those with <70% loss were considered mineral (Scottish Soils Database). Once segregated, the organic and mineral soils were weighted vertically based on bulk density and depth, resulting in aggregated soil parameters for each compartment. This procedure was repeated for all soil types in the catchment. Finally, all soils in the catchment were spatially weighted to generate the lumped organic and mineral soil parameters necessary for two-layer MAGIC calibrations at the catchment scale.

Net uptake of ions in biomass at afforested sites was calculated relative to the age and spatial coverage of forest within the catchment (Hamilton and Christie, 1971). Base cation uptake from the soil pool was proportioned relative to the fine-root density of the two soil compartments. Although data on fine-root densities are not available for the UKAWMN sites, forest floor fine-root biomass is generally negatively correlated with increasing acid deposition (Gundersen *et al.*, 1998). A study of fine-root densities at Gårdsjön (south-west Sweden), concluded that 75% of fine roots are present in organic forest soil (Gundersen *et al.*, 1998). As base cation uptake is proportional to the fine root density, it can be assumed that 75% of uptake comes from the organic soil and 25% from the mineral soil.

Annual catchment rainfall volumes were based on Institute of Hydrology interpolation of Meteorological Office 1989–92 data at a 10 km^2 resolution. Evapotranspiration (ET) is assumed to vary between 10% of rainfall for a moorland catchment and 20% for a fully forested catchment, scaled linearly relative to the percentage forestry (Jenkins and Cosby, 1989; Robson *et al.*, 1991). Old Lodge (site 13) in south-east England is the only lowland site in the network where low rainfall and high temperatures results in high ET (c. 50%).

FUTURE DEPOSITION AND LAND USE SCENARIOS

Atmospheric transport and deposition models have been used to target the emission sources which have the greatest impact on acid sensitive areas. One such model is the Hull Acid Rain Model (HARM) which is a source-receptor deposition model developed from the Harwell Trajectory Model (HTM) (Derwent *et al.*, 1988). This meteorological model incorporates the principal ions responsible for acid deposition (including SO_2, NO_x, NH_x, and HCl), at a 20 km^2 spatial resolution (Metcalfe and Whyatt, 1995). For all MAGIC simulations, forecast sequences were set up for the AWMN sites based on HARM modelled present-day anthropogenic S deposition and predicted deposition for the years 2005 and 2010 (in conjunction with the Second S Protocol).

Two forestry (land use) scenarios have been considered based on likely land use management practices. Scenario 1 (SC1) involves the removal of mature forest 50 years after planting, with no further replanting, and scenario 2 (SC2) concerns the establishment of new stands immediately upon removal of the mature crop (50 years). The spatial extent and age of forest under scenario 2 is identical to present day after 50 years.

THE MAGIC MODEL

The structure of the MAGIC model is described in detail by Cosby *et al.* (1985a,b). Jenkins *et al.* (1997) give a full description of the calibration procedure used in the one-layer application to the AWMN sites. Within the model, allowance is made for ion exchange processes involving base cations (BC), inorganic aluminium and sulphate, and for weathering reactions within the soil. The parameterisation procedure described by Jenkins *et al.* (1997) was modified to include two soil layers with nutrient uptake proportioned between the organic and mineral layers. Water was routed through the organic and mineral compartments before entering the stream/lake. Implications of hydrological flow routing on surface water chemistry were found to be small in previous MAGIC simulations for the Allt a' Mharcaidh catchment (site 2) and the Round Loch of Glenhead (site 7) (Jenkins and Cosby, 1989). This was attributed to the annual time-steps within MAGIC, which were considered to be insensitive to short-term variations in surface-water chemistry (Neal *et al.*, 1992). Mean surface water chemistry (1988–94) and soil chemistry data were used to calibrate the model.

To calculate soil critical loads for the organic compartment, the calibrated model was used in predictive mode to determine the S deposition required to achieve the soil BC:Al ratio of one at a specified time in the future (50 years). MAGIC was then run repeatedly with different levels of deposition until the chemical criterion was met, and this level of deposition was regarded as the critical load for S.

Results and discussion

COMPARISON OF ONE AND TWO LAYER MODEL APPLICATIONS

The model was calibrated successfully to 21 of the 22 sites in the AWMN in that simulated present-day soil and surface water chemistry compared favourably with observed data. Inadequate soils data for the River Etherow in Yorkshire resulted in the omission of this site from the calibration procedure. Simulated surface water pH varied considerably during the period 1851–2041, and between the one and two layer applications. Sites which are currently acidified apparently changed most from 1851, with the exception of Old Lodge (site 13), which has the lowest simulated pH (Fig. 2a). While the deposition of non-marine S is low at Old Lodge, the geology is dominated by Ashdown sands. The low buffering capacity of these sands and the podzolic soil overlying these sands, contribute to stream acidification at this site. Throughout the simulation period, the two-layer model predicts more acid surface waters compared to the one-layer model (Fig. 2a, b, c). In particular, simulated surface water pH for present day (1997) and in 2041 for Afon Gwy (site 18), Round Loch of Glenhead (site 7), Narrator Brook (site 14) and Lochnagar (site 4) was more acid in the two-layer simulations. Obvious differences exist between the two model structures with regard to soil base saturation, which was lower in the mineral compartment of the two-layer model than the one-layer model throughout the simulation period.

Weathering rates

The combined optimised base cation weathering rates from the organic and mineral soil compartments were generally higher than one-layer weathering rates. Two-layer MAGIC predictions should respond more quickly to reduced sulphur emissions (Second S Protocol). Other variables such as soil depth and cation exchange capacity (CEC), however, can affect the extent of acidification and recovery. For the AWMN sites, average weathering rates were 14 times greater for the mineral compartment compared with the organic compartment. Generally, the small temporal changes in soil base saturation of the mineral compartment at all sites indicate that these mineral soils are the main source of base cations in the buffering process.

COMPARISON OF BASE SATURATION OVER THE SIMULATION PERIOD

With the exception of the sites located in Northern Ireland (sites 19–22) and Narrator Brook (site 14), base saturation was higher in the organic compartment than in the mineral compartment throughout the simulation period (1851 to 2041). Soils with low bulk density (<300 kg m^{-3}), high

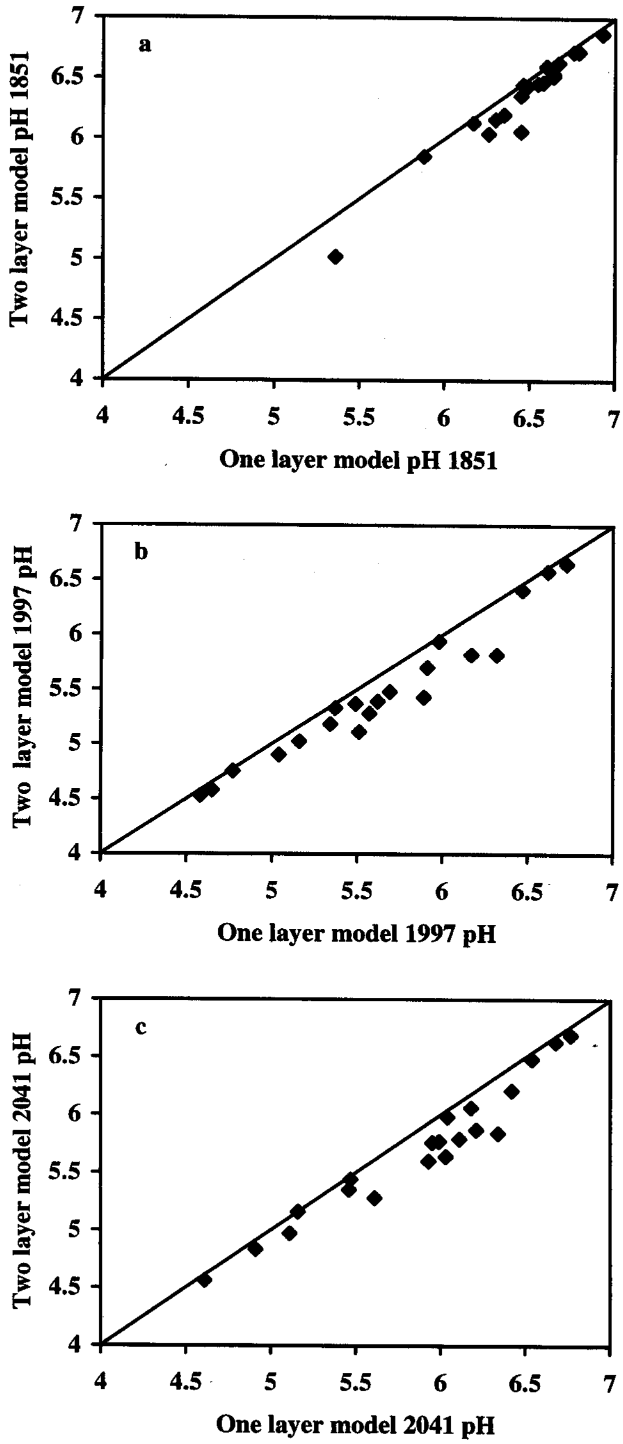


Fig. 2. *Comparison of one and two layer MAGIC simulated surface water pH for a) 1851, b) 1997 and c) 2041.*

organic matter contents, and high CEC are very responsive to changes in deposition (Smith *et al.*, 1993). In 1851, acid inputs were negligible and base cations derived from atmospheric deposition interact with exchange sites in the organic soil complex. With time, increasing acid deposition depletes base cations from the exchange complex resulting in rapid loss of cations predominantly from the organic compartment. for all sites in the network was 14% between 1851–1997 (Fig. 3a). The low selectivity coefficients of the organic soil indicate that remaining base cations are held tightly in the exchange complex. Generally, sites with the highest simulated base saturation (>40% in 1851) in the organic soil are predicted to acidify the most. This is not so apparent for the mineral horizons, although Bencrom River (site 20) and Blue Lough (site 21) are exceptions (Fig. 3b).

MAGIC predictions were made at AWMN sites using the appropriate HARM predicted deposition reductions for non-marine S in line with the Second S protocol (Metcalfe *et al.*, 1995). From 1997 to 2041, sites begin to show signs of recovery (mean increase in base saturation of 2%) in response to the Second S Protocol and from base cation retention in the organic compartment from atmospheric deposition (Fig. 3c). Recovery of soil base saturation in response to S deposition reductions is evident at 18 of the 21 sites. There is no evidence of recovery however, at Loch Grannoch (site 8) and Lochnagar (site 4), where continued deterioration of the base cation status is indicated. Here, the level of sulphur deposition, although reduced, continues to exceed the supply of cations from weathering processes. The mineral layers are less responsive to changes in deposition. The model predicts further deterioration in the base saturation of mineral soils from 1997 to 2041 for all sites in England and Wales, and Lochnagar (site 4) and Loch Grannoch (site 8) in Scotland (Fig. 3d). Clearly, more drastic measures may be required to reverse the acidification at these sites.

IMPLICATION FOR FORESTRY PRACTICES

Five sites in the AWMN are afforested, ranging from 42% at Allt na Coire nan Con (site 1) to 78% at Llyn Cwm Mynach (site 16). Two scenarios of land use change have been used to assess the impact of future forest management schemes on soil and water quality given proposed changes to S emission reductions.

The predicted impact of forestry on base saturation status of the organic and mineral compartments emphasises the importance of forestry practices in acid sensitive areas. Predicted soil acidity varied from site-to-site as a result of the agreed S reductions, land use scenarios and uptake from the organic and mineral horizons. In 2041, under scenario 1 (SC1), organic forest soils show signs of recovery is base status compared to the mineral soils (Fig. 4a). This is despite a more limited modelled uptake of base cations from the mineral compartment. On planting a second rotation crop (scenario 2, SC2), the predicted recovery of base saturation in the organic compartment is suppressed by demand on the base cation pool from tree uptake (Fig. 4b). In addition, the tree canopy is extremely efficient at filtering pollutants from the atmosphere, and in circumstances where incoming S deposition is greater than base cation

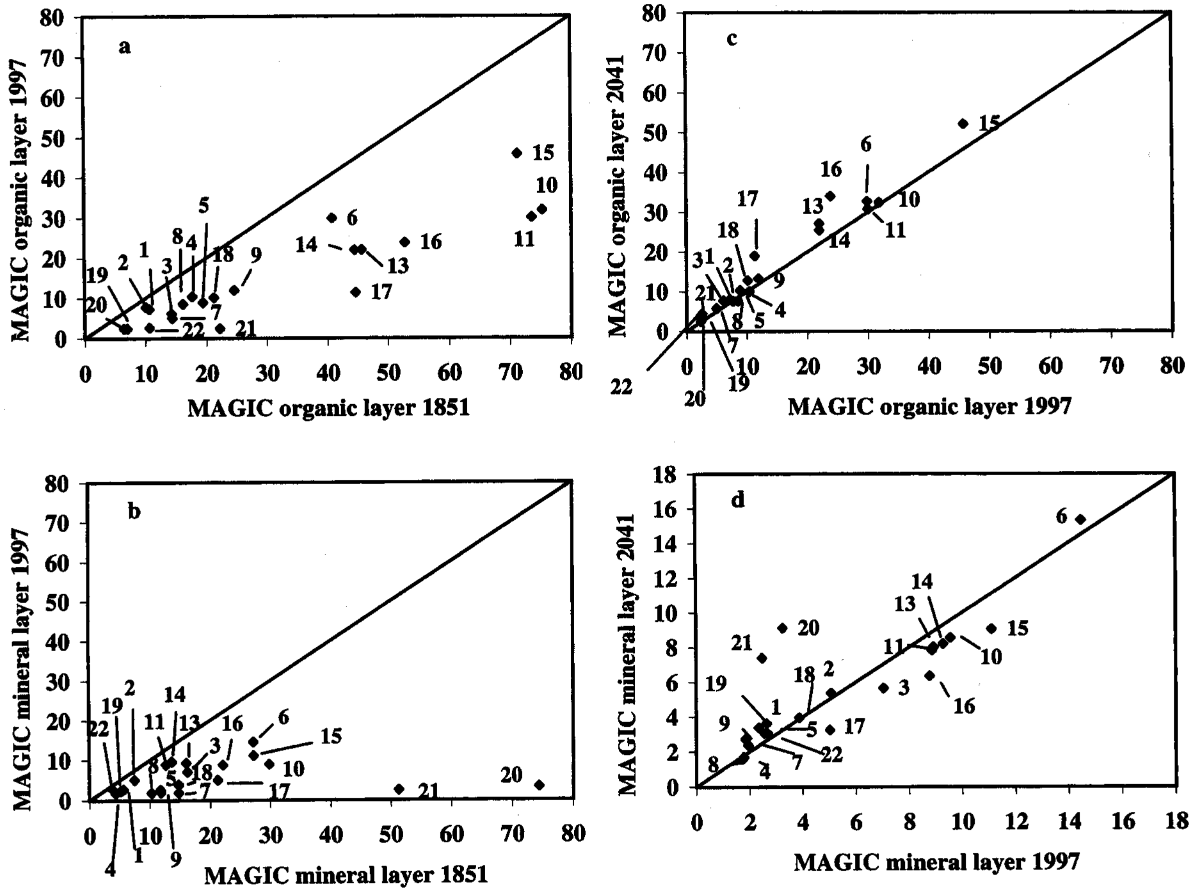


Fig. 3. *Comparison of two-layer MAGIC simulated background (1851) and present day (1997) base saturation for the a) organic and b) mineral compartments; and comparison of MAGIC simulated present day and forecast predictions (2041) of base saturation for the c) organic compartment and d) mineral compartment. Units are % of CEC for soil BS.*

supply from weathering, the soil base saturation will be slow to recover. With the second rotation forest (scenario 2), mineral soils at the most acidic sites (Loch Grannoch (site 8), Loch Chon (site 5) and Afon Hafren (site 17)) are predicted to acidify further, with base cation uptake exerting additional stress on the soil base cation supply (Fig. 4b). Although higher weathering rates supply base cations to the mineral soil, these ions are readily leached in the absence of exchange sites. This is reflected in MAGIC by the generation of high selectivity coefficients for base cations in the mineral soil compartment.

With respect to temporal changes in base saturation, the one and two-layer models both indicate an accelerated decrease in soil base saturation between 1940–80. Consequently, changes in land use management, such as afforestation, aggravate the already serious problem of increasing acid deposition. Comparison of forestry scenarios 1 and 2 at Llyn Cwm Mynach (site 16) demonstrates further soil acidification in both organic and mineral compartments, with a second rotation forest. The organic compartment was very responsive to reduced deposition following clear felling 50 years after planting (scenario 1, Fig. 5a). This suggests that organic soils with high initial base saturation acidify rapidly, yet these soils are the first to recover in response to reduced S deposition associated with S emission controls. Llyn Cwm Mynach (site 16) however, was anomalous in this respect, as the base cation status in 1851 was exceptionally high (52%). This may be a result of high deposition of Mg and Na derived from marine origin. At this time, it was also feasible that low SO_4 concentrations of marine origins were removed from the soil through uptake processes. Present day simulated uptake from the organic compartment was three times greater than uptake from the mineral compartment (94 meq m^{-2} yr^{-1}), although the impact of uptake on the total base cation pool of the organic compartment was relatively small.

In contrast, at Allt na Coire nan Con (site 3) prior to 1997, the base cation status of the mineral compartment exceeded that of the organic compartment, a reflection of the supply of base cations derived from the high weathering rate at this site (86 meq m^{-2} yr^{-1}). In this instance, the base saturation of the mineral soil declined in response to deposition of acid anions and the low CEC. Between 1997

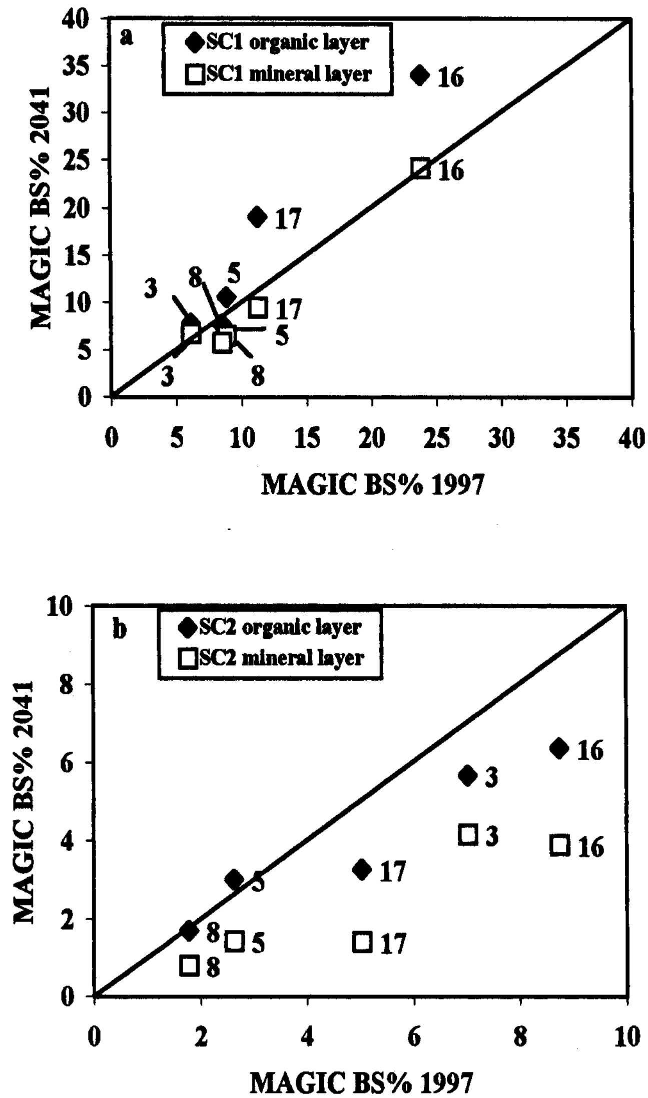


Fig. 4. *MAGIC predicted change (1997–2041) in base saturation under alternative forest management strategies for a) scenario 1 and b) scenario 2 for the organic and mineral soil layers. Units are % of CEC for soil BS.*

and 2041, although the degree of acidification predicted under scenario 2 (second rotation forest) is lower than at Llyn Cwm Mynach (site 16), the mineral soil shows greater acidification (i.e. lower base saturation) than the organic soil (Fig. 5b). Where mature forest is removed with no further planting (scenario 1), the base saturation of the organic compartment recovers steadily in response to reduced S emissions. Under the scenario involving a second phase of planting (scenario 2), the soil base saturation barely recovers even in the situation of reduced S deposition (Fig. 5b). Although the extent of acidification at Allt na Coire nan Con (site 3) exceeds that of Llyn Cwm Mynach (site 16) in 1851, the change in soil acidity from 1851 to 2041 is much less for Allt na Coire nan Con (site 3) than Llyn Cwm Mynach (site 16).

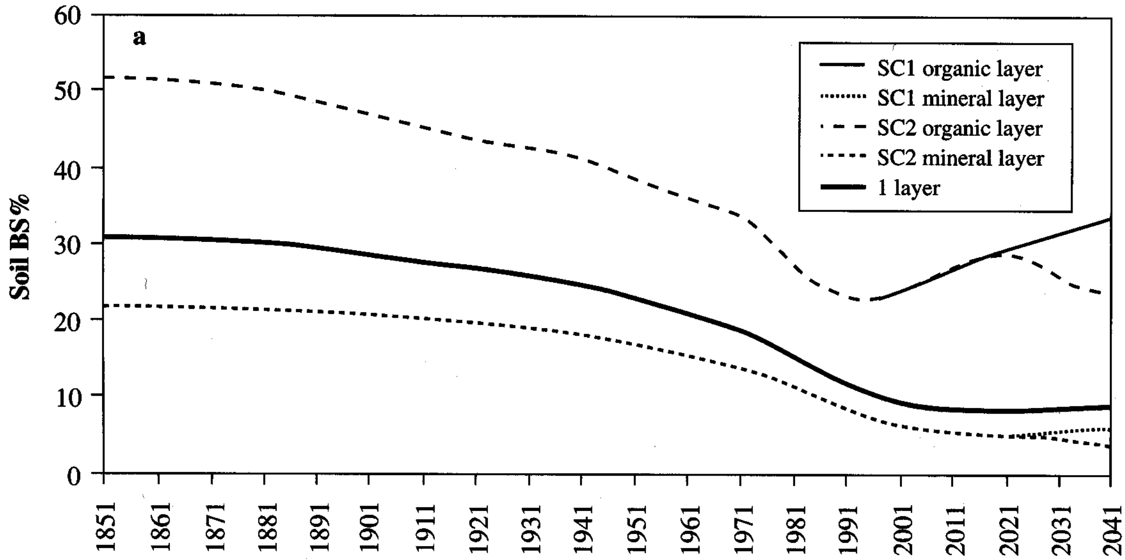
Present day (1997) base cation fluxes from uptake, weathering and deposition in the organic and mineral compartments (Fig. 6) indicate a greater loss of base cations through uptake from the organic compartment than from the mineral compartment. The base cation flux from weathering was greater in the mineral compartment than the organic compartment for all afforested sites. Deposition fluxes were variable at all sites and were independent of the extent and age of forestry. Furthermore, there appeared to be no relationship between the deposition and uptake fluxes of base cations in the two soil compartments. The importance of base cations derived from atmospheric deposition far exceeds other sources and fluxes of base cations at the afforested sites (Fig. 6).

SOIL CRITICAL LOADS

Dynamic models represent a robust objective tool for examining the time required for soils to recover from exceedance. Soil base saturation (BS), and the molar ratio of Ca^{2+} + Mg^{2+} + K^{+} (BC) to Al^{3+} in soil solution are indicators of soil acidification. Soil with a BC:Al ratio below 1 is considered to be severely acidified leading to fine-root damage (Jönsson *et al.*, 1994; DOE, 1994). Although other dynamic models, such as SAFE, simulate a critical load for individual soil horizons in the profile (Jönsson *et al.*, 1994), in this study critical loads were calculated by MAGIC for the organic compartment only. MAGIC critical loads were calculated as the present day (1997) deposition of S required to produce a BC:Al > 1 within a time scale of 50 years.

Critical load exceedance (where deposition is greater than the soil critical load) was apparent for the organic soil at the forested sites of Llyn Cwm Mynach (site 16), Afon Hafren (site 17), Loch Grannoch (site 8) and he acid sensitive moorland sites of Dargall Lane (site 9), Lochnagar (site 4) and Old Lodge (13) (Fig. 7a). Results from the one-layer aggregated model, however, indicated that the soil critical load was not exceeded at any site. The organic compartment in the two-layer model is a more sensitive receptor to acid deposition compared to the one-layer approach. There was no direct correlation between soil critical load and present day (1997) deposition for either the one or two layer model.

In 1997, soils were severely impacted, with BC:Al ratios < 1, in the organic horizons at seven sites (Loch Chon (site 5), Loch Tinker (site 6), Dargall Lane (site 9), Old Lodge (site 13), Llyn Cwm Mynach (site 16), Afon Hafren (site 17) and Afon Gwy (site 18)). By 2041 only two sites, Loch Chon (site 5) and Loch Tinker (site 6) are predicted to have BC:Al < 1. Both of these sites have thick organic layers, and thus recovery is slow (Fig. 7b).



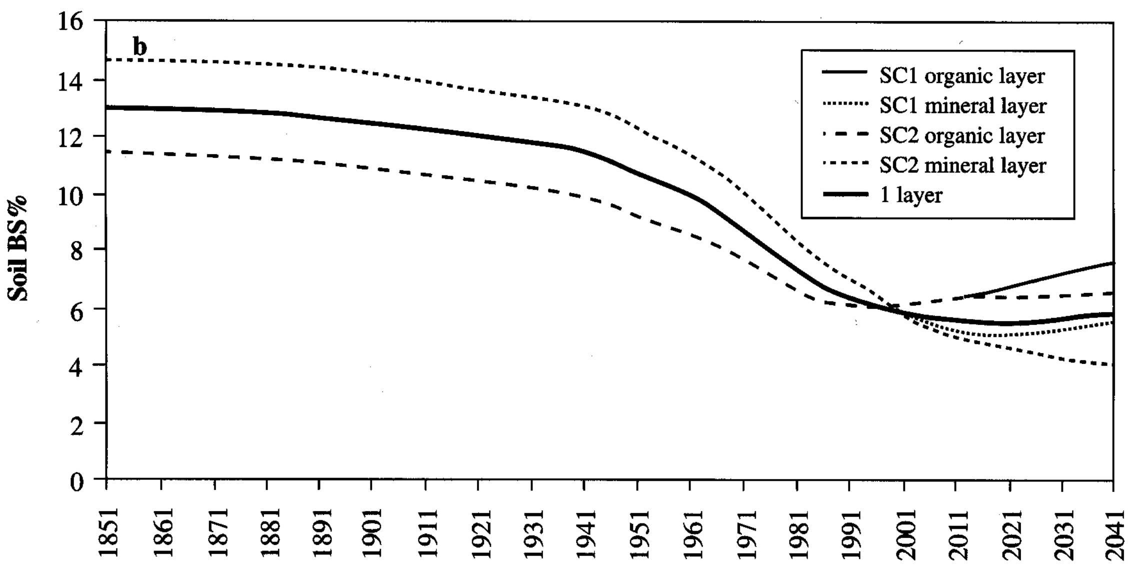


Fig. 5. *Long term response of soil base saturation to the Second S Protocol, and forestry management practices (scenarios 1 and 2) for one and two layer models, a) Llyn Cym Mynach b) Allt na Coire nan Con. Units are % of CEC for soil BS.*

CRITICAL LOADS AND EFFECTS OF AFFORESTATION

The soil critical load threshold (BC:Al ratio = 1) was originally established to protect trees of conservation value. In the absence of a better criterion, this threshold was applied to commercial forests in the five afforested sites in the network. In assessing growth rate reductions and estimating the costs of reduced forest productivity due to soil acidification, the relationship between BC:Al ratio and tree growth is important (Sverdrup *et al.*, 1993). Critical loads for soils were found to vary with forest management strategy. The impact of forestry was particularly significant on the more sensitive sites, dominated by base poor soils (Fig. 4a and b). Afforestation resulted in enhanced acidification of organic soils from forest uptake and interception and this was reflected by low critical loads. Soils recover from acidification after the removal of forest (scenario 1), but replanting accelerates acidification of the organic soil. Estimates of exceedance of soil critical loads for 2041 under scenarios 1 and 2 are lower as a result of the Second S Protocol, for all forested sites except Loch Grannoch (site 8). Naturally, scenario 1, involving the

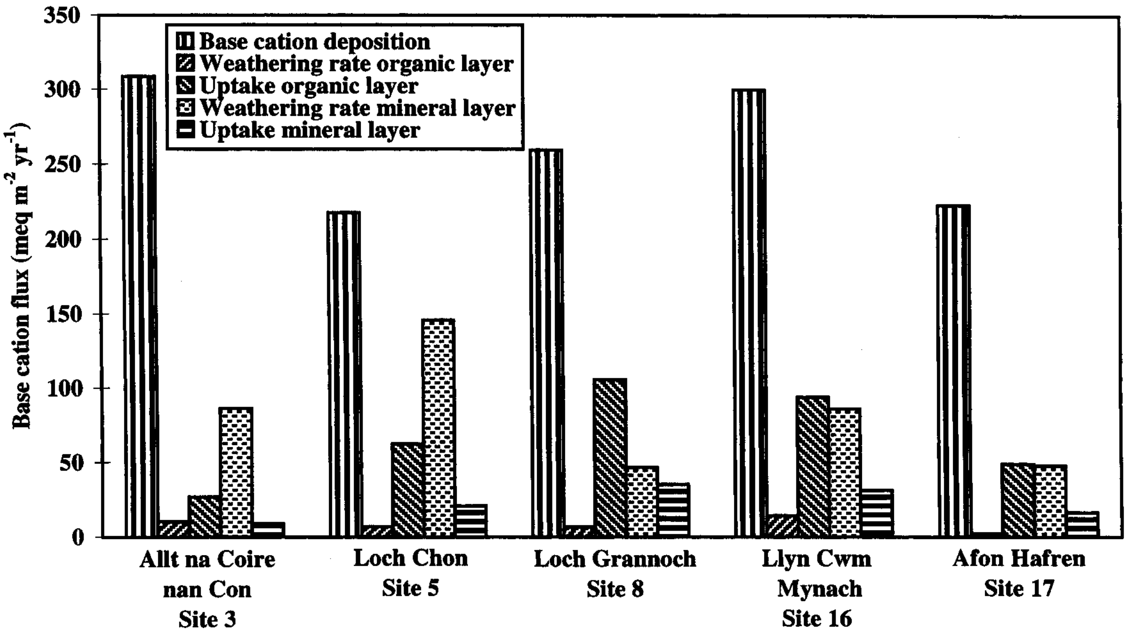


Fig. 6. *Comparison of MAGIC simulated present day base cation fluxes for the organic and mineral soil layers. Unit meq* m^{-2} yr^{-1}.

(a)

(b)

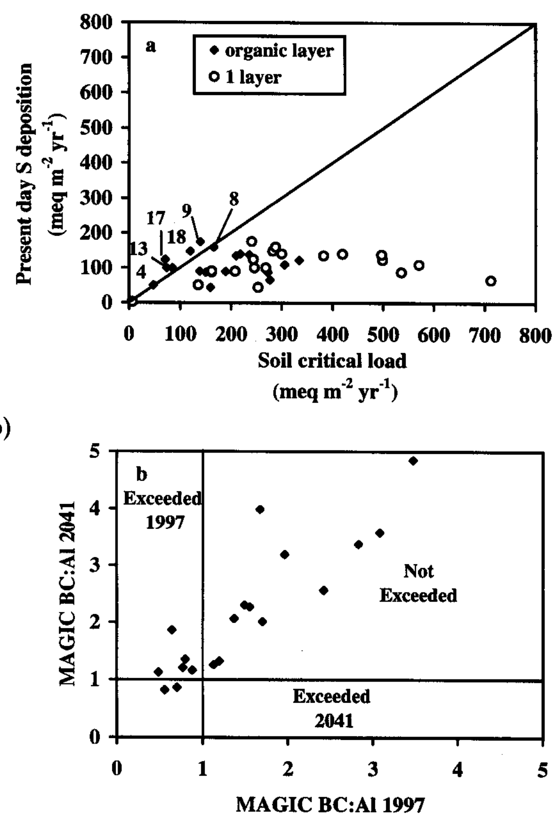


Fig. 7. *a) MAGIC critical loads calculated for soil BC:Al of 1 for the one-layer model and the organic compartment of the two-layer model. b) MAGIC predicted change from present day (1997) to 2041 of BC:Al ratios. The critical load is exceeded for those sites below the threshold of 1. (Units: meq* m^{-2} yr^{-1}*).*

removal of mature forest with no replanting, indicates significant recovery at all forested sites while recovery is less pronounced with replanting (scenario 2). However, further reductions in S emissions, beyond those already agreed under the Second S Protocol, are necessary if afforested sites under a second rotation of forestry are to recover adequately (i.e. BC:Al > 1) by 2041. With the exception of the least acidified forested site (Allt na Coire nan Con, site 3), these results (Fig. 8) highlight the need for proactive and responsible forestry management policies, particularly with regard to control of replanting (scenario 2), consistent with the longer term objectives of protecting and sustaining soil and water quality. Recovery of BC:Al ratios appears to be related to the present day (1997) acid status of the soil, as sites with present day soil BC:Al ratios < 1 (under scenario 1) show the greatest predicted recovery in 2041. However, this is not the case at Loch Grannoch (site 8) where the predicted BC:Al ratio decreases from present day, indicating that incoming S continues to exceed the supply of base cations to the soil system through weathering processes.

Organic soil tend to be more sensitive to acid deposition than surface waters. The one and two layer models predicted that the surface water critical loads were exceeded at a similar number of sites (Fig. 9). With anticipated reductions in S emissions of up to 80% by the year 2010 (Second S Protocol), both one and two layer models predict recovery of surface waters by 2010 as indicated by fewer sites exceeding the critical load. Predictions of soil critical loads appear to be optimistic with the one-layer model, as they indicate that the soil BC:Al ratio is greater than 1 for all sites in the network. The organic soils are

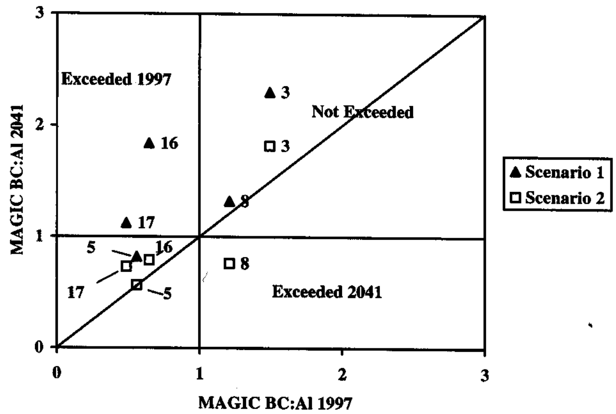


Fig. 8. *MAGIC PREDICTED BC:Al ratios under alternative forestry management strategies (scenarios 1 and 2) for present day (1997) and forecast predictions (2041).*

more sensitive to acid deposition inputs, with the two-layer model indicating 38% of sites exceeding the critical load in 1997. At two sites (Loch Chon (site 5) and Loch Tinker (site 6)) however, the organic soils failed to recover by 2010 in response to the agreed S Protocol. The number of sites exceeding the critical load for surface waters was similar under one and two layer model applications in 2010.

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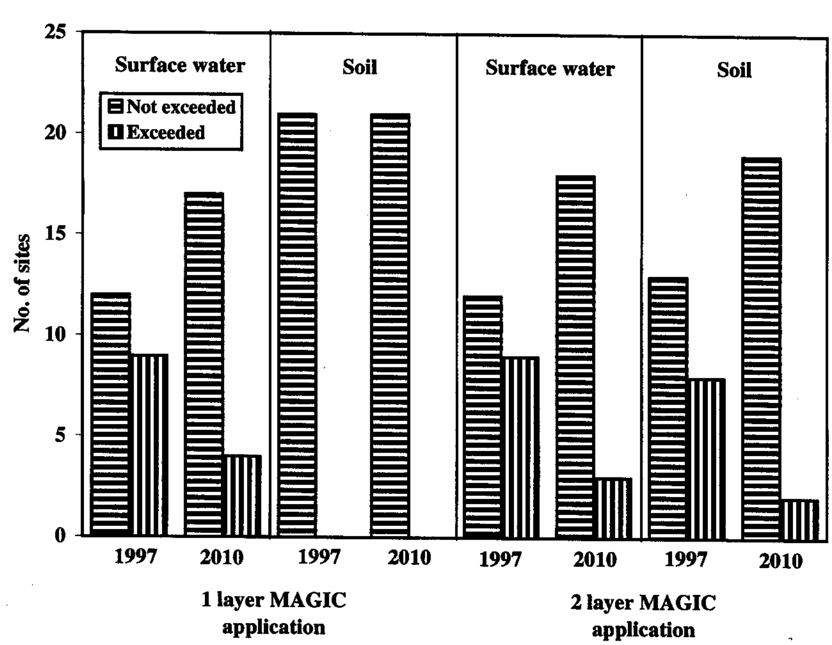

Fig. 9. *Comparison of critical load exceedance for soil and surface waters from the one and two layer models.*

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