Optlime, a bioecenomic model of soil acidity management in agricultural systems

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Contents

Disclaimer ....................................................................................................................... 2
Acknowledgements ........................................................................................................ 2

Overview of Optlime ..................................................................................................... 2
  What is Optlime? ........................................................................................................... 3
  How do I use Optlime? ................................................................................................. 3

‘Site & soil’ page screenshots and instructions .............................................................. 4
  Step 1. Initial soil characteristics ................................................................................. 4
  Step 2. Rainfall zone and nitrate leaching assumptions ............................................. 4
  Step 3. Land use .......................................................................................................... 5
  Step 4. Potential yields, commodity prices and discount rate .................................... 5
  Step 5. Application rates of acidifying fertilisers and contribution of nitrogen from legumes 6
  Step 6. Cost of surface application of lime ................................................................. 6
  Step 7. Cost of deep banding lime ............................................................................. 7

‘Apply lime’ page screenshots and instructions ............................................................ 8
  Step 1. Define lime sources and strategies .................................................................. 8
  Step 2. View result charts ............................................................................................ 9
  Step 3. View mass balance table ................................................................................ 10
  Step 4. View investment appraisal ............................................................................. 10

Explanation of investment appraisal components ......................................................... 11
  Sum of discounted benefits and sum of discounted costs ........................................... 11
  Net present value ....................................................................................................... 11
  Benefit cost ratio ....................................................................................................... 11
  Internal rate of return ................................................................................................. 11
  NPV, BCR or IRR? A note on the choice of investment criterion ................................. 11

Technical description .................................................................................................... 12
  Lime quality representation ....................................................................................... 12
  Dissolution of CaCO$_3$ .............................................................................................. 13
  pH change and leaching of excess alkali ................................................................. 13
  Yields ......................................................................................................................... 14
  Acidification rates ..................................................................................................... 15
  Benefits and costs of liming ...................................................................................... 16
  Investment analysis .................................................................................................. 16
  Discounted benefits and costs of lime ....................................................................... 16
  Net present value and benefit cost ratio ................................................................... 16
  Internal rate of return ............................................................................................... 17
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Overview of Optlime

What is Optlime?
Optlime is a model that represents the essential biological, physical and economic factors related to soil acidity management in Western Australia. The model allows users to define site and soil characteristics for an acidic scenario and then simultaneously assess likely outcomes for 2 different lime sources and application strategies. With and without liming scenarios are examined over a 20 year simulation so as to capture the long-term impacts of soil acidity management. Output provided allows you to examine the likely effect of liming on pH, exchangeable aluminium, yields, and profits. An investment appraisal is provided to show you how liming might stack up financially using a variety of time horizons.

Optlime is not a lime recommendation tool, and should never be used as one. In practice, responses to liming for apparently similar situations can be very variable. The simplifications in the model do not allow us to fully account for this variability. For this reason, Optlime should be seen as an aid to understanding the management of soil acidity, not as a recipe.

How do I use Optlime?
Optlime consists of 5 sheets:

1. 'Overview' (general introduction)
2. 'Site & soil' (for entry of details related to soil characteristics, climatic zone, land use pattern etc)
3. 'Apply lime' (for entry and comparison of lime sources and application strategies, and for viewing model output)
4. 'Soil model' (detailed calculations of lime dissolution, lime leaching and acidity amelioration; this sheet is for viewing only)
5. 'Cashflow' (detailed calculation of yields +/- lime and associated cashflows; this sheet is for viewing only)

To begin using Optlime, navigate to the 'Site & soil' sheet and follow the instructions provided for data entry. Where applicable, default values are provided to aid in this process. Next, navigate to the 'Apply lime' sheet and follow the instructions there for defining of lime sources and application strategies. Summary results are provided on the 'Apply lime' sheet, while detailed calculations can be viewed on the 'Soil model' and 'Cashflow' sheets.
‘Site & soil’ page screenshots and instructions
The ‘Site & soil’ section of Optlime is where you define the scenario for which you wish to assess liming. There are 7 tables of information to fill out. Default values are provided where appropriate.

**Step 1. Initial soil characteristics**

Enter soil details for each 10 cm layer. The soil texture description is used by Optlime in the calculation of default nitrate leaching and to determine the distribution of acidification through the soil profile. The gravel%, organic carbon and exchangeable aluminium ($\text{Al}^{3+}$) class are used to calculate pH buffering capacity. The exchangeable $\text{Al}^{3+}$ class is also used in the calculation of yield impacts of acidity in the 10-20 cm and 20-30 cm soil layers. Levels of toxic aluminium are very difficult to predict, so for the purposes of Optlime we assume 3 broad classes of $\text{Al}^{3+}$. Many soils in the WA wheatbelt would fall into the 'moderate' category. The 'low' category would apply to paler sandy soils, while the 'high' category is representative of eastern wheatbelt wodjil soils. The bulk density of the soil is used in the calculation of pH buffering capacity and saturated water content (for lime dissolution calculations).

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>0-10 cm</th>
<th>10-20 cm</th>
<th>20-30 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil texture</td>
<td>Sand-loam</td>
<td>Loam</td>
<td>Loam</td>
</tr>
<tr>
<td>Gravel %</td>
<td>5.0%</td>
<td>20.0%</td>
<td>20.0%</td>
</tr>
<tr>
<td>Initial pH ($\text{CaCl}_2$)</td>
<td>4.80</td>
<td>3.90</td>
<td>4.40</td>
</tr>
<tr>
<td>Organic carbon %</td>
<td>1.0%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Exchangeable $\text{Al}^{3+}$ class</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Bulk density (g/cm$^3$)</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>Saturated water content</td>
<td>42%</td>
<td>42%</td>
<td>42%</td>
</tr>
</tbody>
</table>

**Step 2. Rainfall zone and nitrate leaching assumptions**

Select the average annual rainfall zone that best matches the site in question. A saturated soil scenario is also available to allow for assessment of lime dissolution under conditions of constant soil moisture.

Optlime calculates a default value for nitrate leaching based on the selected rainfall zone and soil texture. This default value represents a long-term average. Actual nitrate leaching will vary significantly from year to year depending on the frequency, intensity and timing of rainfall.
**Step 3. Land use**

Use the option boxes provided to construct a land use rotation of between 1 and 5 years. The rotation that you define will be repeated throughout Optlime's 20 year simulation. If the rotation is less than 5 years in length, then select the 'Nil' option for subsequent years. For example, a sequence of 'wheat, lupins, nil, nil, nil' would feed into the model as a repeating wheat / lupin rotation. The wool and meat options are assumed to represent a legume-based pasture phase. Each crop or pasture enterprise is assigned an 'acidity tolerance class', ranging from 1 (most tolerant) to 8 (most sensitive). The table at right provides a guide to critical pH values for each acidity tolerance class.

**Step 4. Potential yields, commodity prices and discount rate**

The 'potential' yields that you enter in Optlime are intended to represent what would realistically be achievable in a situation where soil acidity is not a limiting factor. Default yields are also provided and can be selected if preferred. Prices entered should be long-term expected values, similar to what would be assumed in a farm budget. A discount rate also needs to be entered. Optlime discounts future values to present dollar terms in order to account for the time value of money. Time value exists because a dollar can be invested today and earn a return, such that at some point in the future the dollar invested will be worth its original value plus the value of accrued returns. It follows then that a dollar in the future is worth less than a dollar now. By discounting it is possible to express future values in terms of net present dollars. There are no hard and fast rules about the selection of discount rates, although for business decisions the weighted average cost of capital is generally used.
Step 5. Application rates of acidifying fertilisers and contribution of nitrogen from legumes

Application of nitrogen in the form of ammonium (e.g. ammonium sulphate, DAP) causes acidification due to the net addition of H+ when ammonium is converted to nitrate. Nitrogen in the form of nitrate or urea is not directly acidifying. However, acidification will occur if any of the nitrogen is leached in nitrate form. The same applies to legume-fixed nitrogen. For each land use, define the application rates of nitrogenous fertiliser in the table below. Legume-fixed nitrogen is calculated automatically by Optlime based on the yield potentials defined at Step 4.

<table>
<thead>
<tr>
<th></th>
<th>Wheat</th>
<th>Beef</th>
<th>Canola</th>
<th>Lupins</th>
<th>Grass</th>
<th>Hay</th>
<th>Wool</th>
<th>Meat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonium sulphate</td>
<td>0.210</td>
<td>3.90</td>
<td>7.10</td>
<td>4.71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DAP (kg/ha)</td>
<td>0.175</td>
<td>1.00</td>
<td>5.40</td>
<td>2.94</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urea (kg/ha)</td>
<td>0.150</td>
<td>0.00</td>
<td>3.56</td>
<td>1.14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid UAN (Brescia)</td>
<td>0.020</td>
<td>1.00</td>
<td>3.60</td>
<td>1.14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Legume-fixed nitrogen (kg/ha)</td>
<td>1.900</td>
<td>0.00</td>
<td>3.60</td>
<td>1.14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Step 6. Cost of surface application of lime

The cost of applying lime is rate-dependent and can be approximated by the curve shown. The cost curve can be raised or lowered by following the instructions provided in the spreadsheet.
Step 7. Cost of deep banding lime

The deep banding of lime is a machinery-intensive operation that imposes a level of wear and tear on equipment over and above most other tillage-based activities. It is therefore important when assessing the feasibility of deep banding to accurately account for the costs involved. This includes not only the direct cash costs of the operation, but also the excess depreciation that is attributable to deep banding.

Tables are provided in Optlime for estimating the costs of deep banding lime. There are two main sections to the calculations. The first section calculates the cash cost component of deep banding. The second section makes allowance for the portion of depreciation attributable to the deep banding operation. For many situations, the default values provided will be sufficiently indicative.
‘Apply lime’ page screenshots and instructions

Step 1. Define lime sources and strategies

The ‘Apply lime’ page allows side-by-side comparisons for two lime sources & application strategies.

Lime product characteristics can be manually entered, or you can load typical values for various WA limes sources. These 'typical' values are general only, and are not intended to represent product from specific lime providers.

Next, enter lime costs, and select a deep banding placement strategy. Then move to the lime applications section and enter rates for topdressed and deep banded lime.
Step 2. View result charts

- Enter year for which you wish to view pH profile...
- ... or use the scroll bar to step forward/ backward 1 year at a time...
- ... or view an animation of the pH profile over the 20 year simulation

Select other charts

Enter pH targets here. These values will appear on all pH charts

Control how the Y-axis of time series charts are displayed
Step 3. View mass balance table

For each lime source and strategy, a mass balance summary is provided to account for the fate of applied lime, expressed in tonnes per hectare of pure calcium carbonate. This summary is derived from the soil model calculation within Optlime. These calculations explicitly represent the dissolution and leaching of lime and its consumption in acidity amelioration.

<table>
<thead>
<tr>
<th>Mass balance of CaCO₃ over 20 years (t/ha)</th>
<th>0-10 cm</th>
<th>10-20 cm</th>
<th>20-30 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaCO₃ applied</td>
<td>1.79</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>CaCO₃ leached in</td>
<td></td>
<td>0.56</td>
<td>0.00</td>
</tr>
<tr>
<td>Total available</td>
<td>1.79</td>
<td>0.56</td>
<td>0.00</td>
</tr>
<tr>
<td>CaCO₃ consumed</td>
<td>1.20</td>
<td>0.56</td>
<td>0.00</td>
</tr>
<tr>
<td>CaCO₃ leached out</td>
<td>0.56</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>CaCO₃ undissolved</td>
<td>0.03</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total accounted for</td>
<td>1.79</td>
<td>0.56</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Step 4. View investment appraisal

Results of the liming investment analysis are provided in a table directly below the charts. The investment in lime can be analysed using any time horizon between 1 and 20 years by adjusting the ‘show results’ cell. A minimum time frame of 5 years is suggested.

An explanation of the components of the investment appraisal is provided below.
Explanation of investment appraisal components

**Sum of discounted benefits and sum of discounted costs**
The annual benefit of lime is taken as the dollar value of any yield increase due to liming. The unlimed scenario is used as a base for this calculation. These annual benefits are discounted into today's dollar terms, and then added up to calculate the sum of discounted benefits. In each year that lime is applied, Optlime discounts liming cost according to the discount rate and the number of years into the future. The sum of discounted costs of lime is the total cost of lime over the specified time horizon expressed in today's dollar terms.

**Net present value**
The net present value (NPV) is the difference between the sum of discounted benefits and the sum of discounted costs. This is the actual net gain from liming expressed in today's dollar terms.

**Benefit cost ratio**
The benefit cost ratio (BCR) is the ratio of total discounted benefits to total discounted costs. Therefore, the BCR is a measure of relative net gain, that is the gain in benefits relative to costs. A BCR of more than 1 indicates that benefits are greater than costs. Less than 1, and the costs have outweighed the benefits.

**Internal rate of return**
The internal rate of return (IRR) is the discount rate at which the present value of benefits equals the present value of costs (i.e. NPV = 0 and BCR = 1). It is a measure of the percentage rate of return of gains over losses and, therefore, is another measure of relative net gain.

**NPV, BCR or IRR? A note on the choice of investment criterion**
The NPV, BCR and IRR all provide a sound means of assessing an investment in lime. Unfortunately, each criterion can rank alternatives differently. So, for example, the liming strategy that maximises NPV may be different from the liming strategy that maximises BCR or IRR. The following guidelines are provided:

- The BCR should be used to select the optimum strategy when the liming budget is fixed - because maximum net benefits are then obtained. This is the criterion that will apply to farmers who are unable or unwilling to expand their liming budget through re-allocation of funds or borrowing.

- In some cases, the budget is not limited or, more often, extra money can be borrowed. This allows us to pursue the strategy that maximises overall net gain, in which case the NPV becomes the criterion of choice. However, additional costs of borrowing do need to be factored in.

- The internal rate of return is useful in terms of telling us the discount rate at which the NPV is equal to zero, therefore providing an indication of the sensitivity of results to the discount rate.
Technical description

A core focus of the 2008 review of Optlime was to improve the representation of lime quality and lime dissolution. This section provides an overview of the key calculations implemented within the Optlime spreadsheet. The lime quality and dissolution calculations adopted draw heavily on work by Craig Scanlan from the University of Western Australia.

Lime quality representation

Lime quality data is represented by particle size distribution and neutralizing value in the same manner as the Lime WA Product Information Sheets (http://www.limewa.com.au/). This approach helps ensure consistency between Optlime and industry standards. Based on these key quality attributes, the surface area of CaCO$_3$ per tonne of product can be calculated. Surface area of CaCO$_3$ then becomes an input to the lime dissolution calculations.

The number of particles in each sieve range per tonne of product is calculated as:

\[ n_i = \frac{\% \text{Weight}_i}{\left( \frac{4}{3} \times \pi \times \left( \frac{d_i}{2000} \right)^3 \times BD_{\text{Lime}} \right)} \]

Where:

- \( i \) refers to the \( i \)th sieve range (of which there are 5 as per Lime WA Product Information Sheets).
- \( BD_{\text{Lime}} \) is the bulk density of lime in t/m$^3$.
- \( d_i \) is the midpoint of the particle size diameter (mm) for \( i \)th sieve range. Note: the divisor of 2000 converts the diameter in mm into radius expressed in metres.
- \( \% \text{Weight}_i \) is the proportion of product that falls into the \( i \)th sieve range.

Having calculated the number of particles in each sieve range per tonne of product and, assuming that each particle is spherical, it is then possible to calculate the surface area (m$^2$) of CaCO$_3$ per tonne of product as:

\[ A = \sum_{i=1}^{5} \left[ 4\pi \times \left( \frac{d_i}{2000} \right)^2 \times NV_i \times n_i \right] \]

Where \( NV_i \) is the neutralising value of product that falls into the sieve range \( i \).
**Dissolution of CaCO₃**

Following Scanlan’s approach, the net rate of CaCO₃ dissolution is calculated as:

\[ R = k(10^{-pH} - 10^{-pH_{\text{Equil}}}) \cdot \theta \cdot 10,000 \]

Where:

- \( R \) is the rate of dissolution in moles / m² / month. Note: Scanlan’s model is a daily timestep rather than monthly.
- \( pH \) is the initial pH of the soil horizon in question.
- \( pH_{\text{Equil}} \) is the ‘equilibrium’ pH, above which CaCO₃ will not dissolve into the soil solution.
- \( \theta \) is a soil water content scalar which can vary between soil horizons and from month to month according to seasonal patterns.
- and where 10,000 is a multiplier that converts the unit of surface area from cm² into m².

Having calculated the rate at which CaCO₃ can dissolve, the net dissolution (t/ha) in any given month, \( t \), is calculated as:

\[ Q_t = \text{Min}\left(\left[R \cdot SA_t \cdot 0.0001, (pH_{\text{Equil}} - pH) \cdot pHBC\right]\right) \]

Where:

- \( SA_t \) is the total surface area of CaCO₃ available per hectare.
- \( pHBC \) is pH buffer capacity in tonnes of CaCO₃ per hectare / pH unit / 10 cm of soil depth
- and the multiplier of 0.0001 converts CaCO₃ from moles/ha to t/ha.

The 2nd part of this equation ensures that the dissolution of CaCO₃ in any monthly timestep cannot exceed the amount that would take the pH of the soil phase above the equilibrium pH. This protective measure only becomes necessary in the event that a user inputs an exceptionally high rate of lime into the model.

**pH change and leaching of excess alkali**

Once the net dissolution of CaCO₃ has been arrived at, an interim pH value can then be calculated:

\[ pH_{\text{Interim}} = pH_{t-1} + \frac{Q_t}{pHBC} \]

A measure of excess alkalinity, \( E \), expressed in t/ha of CaCO₃ equivalent can then be derived:

\[ E_t = \text{Max}[0, (pH_{\text{Interim}} - pH_{\text{Leach}}) \cdot pHBC] \]

Where \( pH_{\text{Leach}} \) is the minimum pH at which excess alkalinity can leach.

Leaching of alkalinity, \( L \), to the next soil horizon can then occur according to the following equation:
A final value of pH for the given time period can then be calculated:

\[ p\text{H}_f = p\text{H}_{\text{interim}} - \frac{L_t}{p\text{H}_{\text{BC}}} \]

The above calculations essentially repeat for each soil horizon. The main difference to note is that subsoil horizons undergo acidity amelioration due not only to lime which is applied directly to the subsoil (by banding), but also from excess alkalinity that leaches in from soil horizons above.

Yields
Optlime calculates yields as the product of potential yield and a yield index, according to the following equation:

\[ Y = PY \times Y_{\text{total}} \]

Where:
- \( Y \) = actual yield (t/ha for crops or kg/ha for livestock products)
- \( PY \) = the potential yield, that is the yield which could realistically be obtained if acidity did not limit production
- \( Y_{\text{total}} \) = a yield index that scales potential yield according to the severity of acidity through the soil profile

The yield index is a value between zero and one, and is calculated as the product of three individual yield indices. These three yield indices represent the 0 - 10 cm, 10 - 20 cm and 20 - 30 cm horizons. Therefore:

\[ Y_{\text{total}} = Y_{0-10\text{cm}} \times Y_{10-20\text{cm}} \times Y_{20-30\text{cm}} \]

The yield index for the 0 - 10 cm horizon is calculated on the basis of pH as follows:

\[ Y_{0-10\text{cm}} = 1 - e^{(-a \times (pH - b))} \]

Where \( a \) and \( b \) are parameters.

The yield indices for the subsoil horizons are calculated on the basis of aluminium toxicity as follows:

\[ Y_{10-20\text{cm} \& 20-30\text{cm}} = a \times \frac{1}{[a + (1 - a) \times e^{(-b \times 1/[Al])}]} \]

Where \( a \) and \( b \) are parameters.
**Acidification rates**

Optlime calculates acidification due to 2 sources:

1. Product removal
2. Nitrogen cycle

Acidification due to product removal is calculated on the basis of yield using the values in Table 1.

**Table 1. Acidification due to product removal.**

<table>
<thead>
<tr>
<th></th>
<th>kmol H⁺ / t or kg</th>
<th>kg CaCO₃ equiv / t or kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>0.045</td>
<td>2.250</td>
</tr>
<tr>
<td>Barley</td>
<td>0.060</td>
<td>3.000</td>
</tr>
<tr>
<td>Canola</td>
<td>0.045</td>
<td>2.250</td>
</tr>
<tr>
<td>Lupins</td>
<td>0.250</td>
<td>12.500</td>
</tr>
<tr>
<td>Grain legumes</td>
<td>0.200</td>
<td>10.000</td>
</tr>
<tr>
<td>Hay</td>
<td>0.600</td>
<td>30.000</td>
</tr>
<tr>
<td>Wool</td>
<td>0.025</td>
<td>1.250</td>
</tr>
<tr>
<td>Meat</td>
<td>0.004</td>
<td>0.175</td>
</tr>
</tbody>
</table>

Acidification due to the nitrogen cycle varies depending on the source of nitrogen and extent of leaching for the scenario in question. A summary of the acidifying effect of various nitrogen sources is provided in Table 2.

**Table 2. Acidifying effect of various nitrogen sources under 0% and 100% leaching.**

<table>
<thead>
<tr>
<th></th>
<th>kg of N per kg or L of product</th>
<th>Acidification due to N cycle (kg CaCO₃/kg N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0% nitrogen leaching</td>
</tr>
<tr>
<td>Ammonium sulphate (kg/ha)</td>
<td>0.21</td>
<td>3.60</td>
</tr>
<tr>
<td>DAP (kg/ha)</td>
<td>0.18</td>
<td>1.80</td>
</tr>
<tr>
<td>Urea (kg/ha)</td>
<td>0.46</td>
<td>0.00</td>
</tr>
<tr>
<td>Liquid UAN (litres/ha)</td>
<td>0.42</td>
<td>0.00</td>
</tr>
<tr>
<td>Legume-fixed nitrogen (kg/ha)</td>
<td>1.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

*Optlime v2008.1 documentation September 2008*
**Benefits and costs of liming**

Optlime calculates the benefit of liming as:

\[
\text{Benefit} = (Y_{\text{limed}} - Y_{\text{unlimed}}) \times P
\]

Where:

- \(Y_{\text{limed}}\) = yield on limed soil
- \(Y_{\text{unlimed}}\) = yield on unlimed soil
- \(P\) = farm gate price of commodity

The cost of applying lime is simply the total of purchase, transport and application costs as defined by the user.

**Investment analysis**

**Discounted benefits and costs of lime**

The total discounted benefits of lime to year \(t\) is the sum of all benefits associated with the liming programme from year 1 to year \(t\), expressed in today's dollars. It is calculated as:

\[
\Sigma_{1\to t}(DB) = \Sigma(B_1 \times DF_1, B_2 \times DF_2, \ldots, B_t \times DF_t)
\]

Where:

- \(B_1, B_2, \ldots, B_t\) are the benefits of liming in years 1, 2, ..., \(t\)
- \(DF_1, DF_2, \ldots, DF_t\) are the discount factors in each year

And where:

- \(DF = (1 + r)^t\),
- \(r\) is the discount rate (as a fraction) and \(t\) is the number of years into the future.

The total discounted costs of lime are calculated in a similar manner to total discounted benefits, i.e. costs in each year are discounted using the appropriate factor, and summed.

**Net present value and benefit cost ratio**

The net present value (NPV), and benefit cost ratio (BCR) of the liming strategy over \(t\) years are:

\[
\text{NPV}_{1\to t} = \Sigma_{1\to t}(DB) - \Sigma_{1\to t}(DC)
\]

\[
\text{BCR}_{1\to t} = \Sigma_{1\to t}(DB) / \Sigma_{1\to t}(DC)
\]

Where:

- \(\Sigma_{1\to t}(DB)\) = total discounted benefits over \(t\) years
• $\Sigma_{1-t}(DC) =$ total discounted costs over $t$ years

**Internal rate of return**
The internal rate of return is the discount rate at which NPV = 0 and BCR = 1. In other words, it is the rate, $r$, at which $\Sigma(DB) = \Sigma(DC)$. Microsoft® Excel uses an iterative process to solve this problem.