- *This report outlines options relating to the use of lime in afforested catchments on acid-sensitive sites in Ireland. It is intended to aid understanding of the issues involved and the practical efficacy of liming.* ***It is not a practice recommendation.***
- *Liming is used to restore the natural conditions of a watercourse to those encountered prior to human influence.*
- *A complete understanding of the flow pathways, residence times and the quality and quantity of runoff is essential for any soil liming project.*
- *In general, reports in the literature tend towards a beneficial effect of liming on fauna and a detrimental effect on vegetation. This is possibly due to the fact that one of the principal aims of liming is to restore fish populations that have been reduced due to acidification.*
- *The use of liming dosers is considered to be the most accurate and precise method of liming under Irish conditions, as the dose is controlled to coincide with times when it is needed most.*

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Liming: a potential option in afforested catchments in Ireland

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What is the problem?

There is a potential risk of surface water acidification in Ireland due to pollutant deposition from more industrialised regions such as the UK and continental Europe. Catchments with acid bedrock are particularly vulnerable. In addition, these effects can be intensified in afforested catchments due to the scavenging of air pollutants by the tree canopy (Fowler 1988, Alexander and Cresser 1995, UK Forestry Commission 2003). Many naturally acid-sensitive waters in Ireland also contain important populations of salmon and trout. Acid waters can have adverse effects on fish by affecting their breathing and reducing growth rate (Ytrestøyl *et al*. 2001).

In Ireland catchments with naturally occurring acid bedrock occur principally along the western coast and in the Wicklow region (Bowman 1991, Figure 1). A study on the interaction between forestry and aquatic ecology in Irish catchments showed that surface waters in heavily afforested sites on granite bedrock had significantly lower pH values (higher levels of acidity) than non-afforested sites

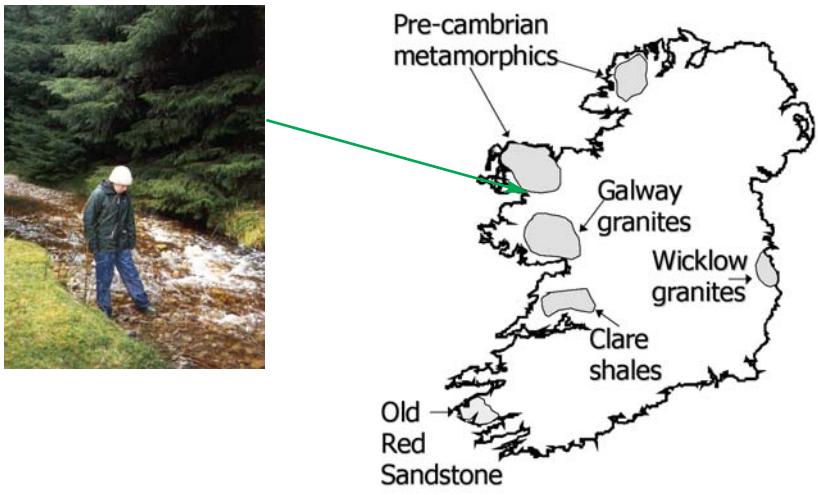

FIGURE 1: Location of naturally acidic waters in Ireland. Typical afforested catchment stream in Burrishole, Co Mayo.

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(Bowman and Bracken 1993, Kelly-Quinn *et al.* 1996, Farrell *et al.* 1997, Kelly-Quinn *et al.* 1997, Allott *et al.* 1997). While this does not prove a cause-effect relationship (forestry tended to be located on the poorest, most acid sensitive catchments in the past) it does indicate that in catchments where afforestation is planned, or has already taken place, measures to address negative impacts should be put in place.

Lime is used in some countries to address the problem

The most effective way to reduce surface water acidification is to reduce emissions of atmospheric pollutants. As a result of the implementation of the Convention on Long-Range Transboundary Air Pollution (CLRTAP) protocol in 1985 there has been a significant reduction in anthropogenic acid deposition in Europe and North America. However, many aquatic sites are showing a significant delay in recovery (Alewell *et al.* 2000) and we are still faced with the problem of acid waters. One method of provisionally reducing acidification in waterways is through increasing pH levels (reducing acidity) by the application of a neutralising material such as lime either directly to the surface waters or to targeted areas of the catchment. Liming has been carried out in catchments in the US, Canada and Europe. However, it must be remembered that lime can also adversely affect ecosystems (Bragg and Clymo 1995, Wickström 2002).

Decision-making

In countries where liming is commonly a part of catchment management, procedures have been developed to help decide whether liming should take place or not (Figure 2). According to Dickson and Brodin (1995), the liming strategy employed should aim to use an inexpensive neutralising material to give the desired effect over as long a period as possible, and that any harmful effects should be kept to a minimum. Liming to alleviate surface water acidification has not been undertaken in Ireland.

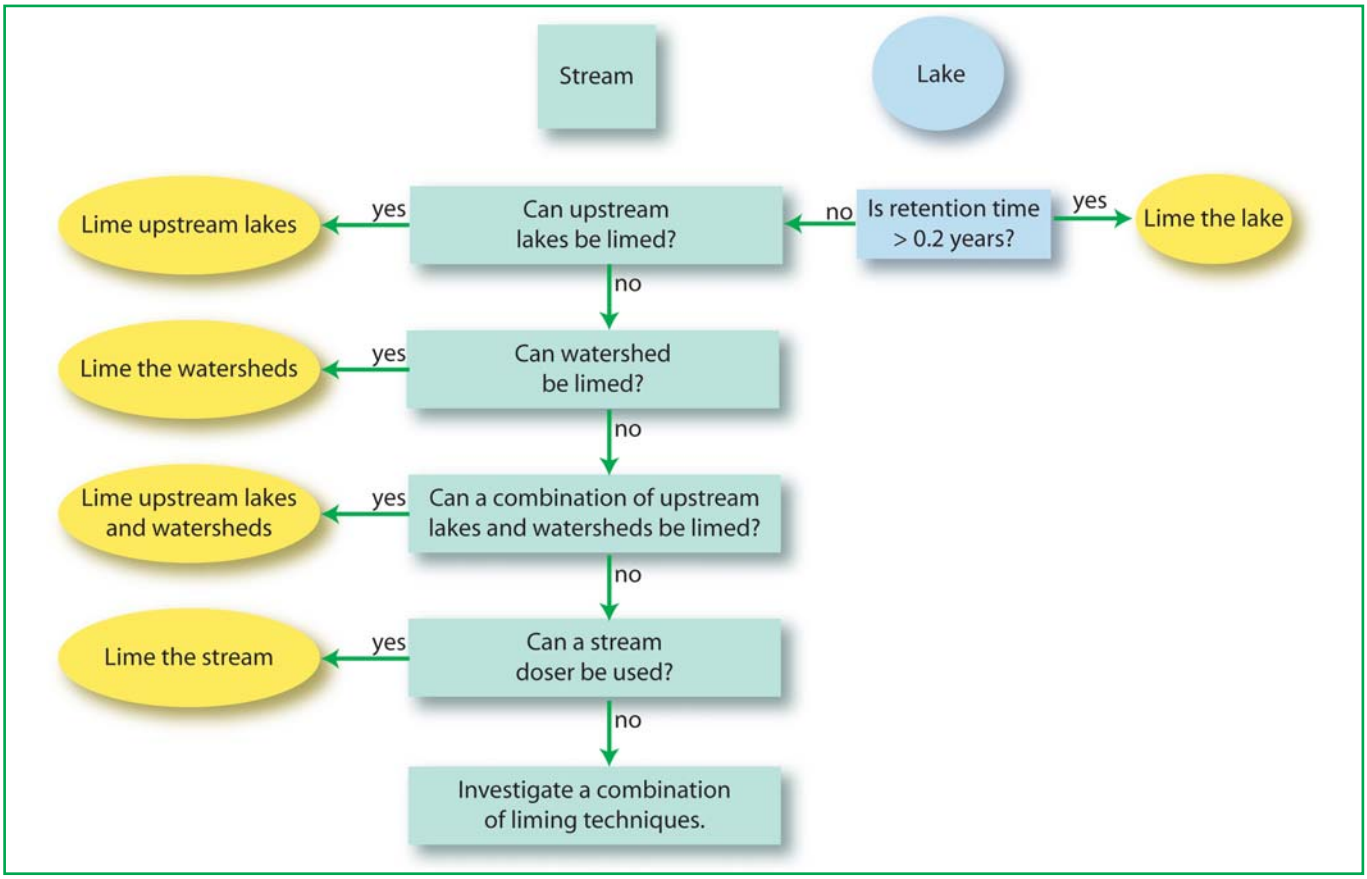

FIGURE 2: Decision strategy developed by the Swedish Environmental Protection Agency for determining liming method (Swedish EPA 1988).

Methods of liming

There are three main methods of liming: lake liming, direct addition to streams, and catchment liming.

Lake liming

Lake liming is carried out to reduce the acidity of a lake or of watercourses downstream of a lake. The effective period will depend primarily on the retention time of the lake and the acidity of the water. Three principal methods of applying lime to lakes are by boat (Figure 3), tractor and aircraft. Table 1 presents the advantages and disadvantages of each method. It is not necessary to lime the entire lake; normally 5-20% of the lake should be targeted with a lime particle size of 0-500 µm diameter (Dickson and Brodin 1995). Small particles sink through the water column more slowly than larger particles and therefore their surface is in contact with the water for a longer time. Doses should not exceed 20 t ha^{-1}. Average application rates in southern Sweden have been reported at 5 t ha^{-1}. Lake liming needs to be carried out at regular intervals. Given the localised nature of forestry cover in Ireland it is doubtful if this technique would have any application.

Stream liming

The pH of a stream varies according to water flow and, in general, pH is lowest at high flows (Davies 1992, Soulsby 1995). The treatment of acid streams is therefore complicated by continuously changing pH and flow and doses should vary accordingly. Liming methods for streams include dosers (Figure 4), direct addition, diversion wells, rotary drums and limestone barriers. Table 2 presents the advantages and disadvantages of these methods.

TABLE 1: Lake liming.

METHOD	ADVANTAGE	DISADVANTAGE
Barge or boat	Simple, inexpensive and accurate.	Access may be difficult. Uneven dispersion.
Truck or tractor	Simple, inexpensive and accurate.	Network of roads needed.
Helicopter	Easy of access to remote areas.	Expensive. Problems with drift.
Aircraft	Easy of access to remote areas.	Expensive. Landing strip required. Drift.

FIGURE 3: Lake liming.

TABLE 2: Stream liming.

METHOD	ADVANTAGE	DISADVANTAGE
Doser	Efficient and accurate. Easily regulated.	High cost. Prone to breakdown.
Direct addition to stream	Immediate effect and cheap.	Effect short-lived. Low constant flow required.
Diversion wells and rotary drums	Simple and inexpensive.	Only useful at low fluctuation in flow and pH.
Limestone bars and barriers	Simple and inexpensive.	Barrier to fish migration. Liable to algae coating.

FIGURE 4: Camddwr lime doser, Wales.

Dosers are used to apply a known amount of lime to a stream. The doser consists of a container for lime storage, a dose control mechanism and a dispensing device. Flow and pH are monitored both up-stream and down-stream of the doser and the amount of lime required to counteract an acid episode is automatically dispensed. It is the most accurate and precise method of liming, as the dose is controlled to coincide with times when it is needed most. Lime particles should be finer than 0.03 mm in diameter.

The direct addition of coarse ground limestone to watercourses is generally found to be inversely proportional to the flow of the stream (Turnpenny 1992). In addition the lime may gradually erode downstream. A diversion well operates by directing water from the watercourse through a tube, to a well containing neutralising material. Rotary drums work by diverting water from the stream into a cylindrical drum that rotates by water-power and contains limestone aggregate. The limestone aggregate neutralises the diverted water before returning it to the stream. Limestone gravel bars and barriers can be used whereby water either passes over a bed of limestone aggregate or flows through a limestone filter. However, small particles tend to fill the gaps between larger particles converting the barrier to a dam. These methods work most effectively at low flow and low fluctuations in pH.

Catchment liming

A thorough knowledge of both catchment soils and hydrology is necessary for a successful catchment liming strategy. Liming of hydrological source areas has been reported to be the most effective method of catchment liming as these are the areas rapidly react to rainfall (Jenkins *et al.* 1991, Waters *et al.* 1991). However, adverse effects on wetland plant communities may render this method unsuitable. Table 3 presents the advantages and disadvantages of catchment liming methods. Trials on liming of buffer strips and riparian areas have been carried out in a small number of studies but none have been considered successful, primarily due to by-pass flow from pre-existing drainage. An integrated approach may be adopted which looks at the catchment as a whole and applies a combination of the most suitable liming methods.

Dose calculations and cost of liming

Various models are used to calculate the dosage required for a particular type of application and whether liming is better applied to a lake, stream or catchment. Some of the criteria used when calculating dosage are rate of dissolution and acidity of the water. In addition, buffering capacity of the soil must be considered in catchment liming.

The cost of liming depends on several factors including the chosen method, the remoteness of the location, dosage required and the frequency of reapplication. The most expensive methods of application are by helicopter, whereas the most cost effective methods are gravel bars and dosers.

Impact of liming on ecology

In general, reports in the literature tend towards a beneficial effect of liming on fauna and a detrimental effect on vegetation. This is possibly due to the fact that one of the principal aims of liming is to restore fish populations that have been reduced due to acidification. In the short term (0-10 years) liming increased growth in productive stands of

TABLE 3: Catchment liming.

METHOD	ADVANTAGE	DISADVANTAGE
Wetland	Inexpensive application.	Adverse effect on flora. High dosage required.
Forest floor	Long effective period of treatment.	Effect not immediate. Access difficult. Negative effect on tree growth.
Spreading from road. Ditch liming. Road construction of lime. Buffer strip/riparian area liming.	Inexpensive. Use of conventional machinery.	Small target area. Limited effectiveness due to hydrology.

Norway spruce and Scots pine whereas growth was reduced in less productive stands. Derome *et al.* (1986) reported a reduction in the annual growth rate of pine and spruce trees in response to liming but these adverse effects could be mitigated through nitrogen fertiliser. Initially, there was a detrimental effect to the *Sphagnum* carpet in a catchment in Scotland after lime was applied as dust. Liming of afforested catchments can cause direct foliar damage due to the alkalinity of the liming material. There is little doubt that liming can restore the ecology of an acidified ecosystem to conditions which closely resemble those that existed prior to acidification but these new conditions will only be sustained as long as liming is continued or acid episodes are prevented.

Recommendations for Ireland

The liming of lakes is only effective where lakes have a relatively long retention time. Most lakes in Ireland have a relatively short retention time and therefore this method will not be recommended for Irish conditions (Table 4). Stream dosers are considered to be a proven technology and are commercially available. They are ideal for Irish conditions because, unlike other stream liming methods, they can handle abrupt changes in pH efficiently and dosing does not occur when the water quality is acceptable. Direct stream liming and diversion wells are potentially useful methods of liming for Ireland. These are found to be effective in very small streams with low flow and little variation in pH. Liming of wetlands has proven to be an effective method of mitigating of acid surface waters in several studies. Because of the potential detrimental effect to the wetland vegetation, in particular to *Sphagnum,* and due to the importance and uniqueness of such habitats in Ireland it is not a recommended liming method.

Forest floor liming in Ireland could be problematic for various reasons. Firstly, access to the forest can be difficult as forests in acid-water catchments may not be thinned or may be at the pre-thinning stage. Secondly, if aerial application were used it is anticipated that it would be prohibitively expensive and the effectiveness would be questionable. Foliar damage and problems of drift would be of great concern if dust-sized particles were used. The use of pellets has been shown to be ineffective in a forest catchment in mid-Wales because the pellets became coated in algae which rendered the lime ineffective (Nisbet 1993).

Several other methods of applying lime to forested catchments have been proposed which would involve the use of the current road network and drains already in existence. Spreading lime directly onto the forest floor from the existing roads using conventional lime spreading equipment would have a very localised effect. Alternatively, limestone-based material could be used for road building. Liming of buffer strips has been attempted in Wales with little success due to the hydrological characteristics and therefore will not be recommended as a liming treatment in Ireland.

TABLE 4: Recommendations for Ireland.

METHOD	RECOMMENDATION			MAIN REASON
	YES	NO	POSSIBLE	
Lake liming		√		Not applicable in Ireland.
Doser liming	√			Proven to be effective in many countries.
Direct stream liming			√	Could work if low flow. Particle size critical.
Diversion well			√	Only suitable at low flow (<1 m^3).
Rotary drum		√		Expensive and problematic.
Limestone bars & barrier		√		Ineffective.
Wetland liming		√		Severe damage to *Sphagnum*.
Buffer zone liming		√		Proven to be ineffective.
Forest floor liming			√	Effective longer-term strategy for soils.
Drain liming		√		Target area too small.
Spreading from roadway		√		Target area too small.
Road constructed of limestone		√		Target area too small.

It would be possible to apply lime to a catchment at the pre-planting stage. This method would be very cost effective and disturbance to the environment would be at a minimum but would be ineffective because the trees would not have reached a stage where they would be scavenging significant amounts of pollutants from the atmosphere. Successful lime spreading could also be performed after the first thinning stage (approximately 15-20 years after planting).

Conclusions

The most promising method of liming for Ireland is the stream doser system as it is a proven technology and is commercially available. Dosers are suited to Irish conditions because the dose rate can be varied automatically in response to changing stream chemistry and so can be timed to coincide with times when it is needed most. Other methods that are worthy of further investigation include the spreading of lime on forest floors and the direct addition of limestone to stream beds.

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