The role of trees in landscape planning to reduce the impacts of atmospheric ammonia deposition

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Abstract

The emission of atmospheric ammonia (NH_3) to the atmosphere and its deposition to ecosystems are highly spatially variable. While national (5 km resolution) maps form the basis of UK policy analysis, landscape level assessments show substantial local structure, with large gradients both adjacent to livestock farm buildings and fertilised/manured agricultural fields. The scale of expected ecological changes are such that it is not feasible to protect all ecosystems in the UK. To maximise the benefit/cost ratio of any NH_3 abatement strategy, it is therefore necessary to prioritise which ecosystems should be protected. Based on such a prioritisation, trees can play an important role in landscape planning to protect priority areas from NH_3 deposition. This is because: trees capture NH_3 at higher rates than other vegetation; they enhance the dispersal of emitted NH_3; and they can shelter sources, thereby reducing NH_3 emissions. Trees may therefore be planted 'sacrificially' around farms or conservation sites, as a strategic re-use of land (e.g., relevant to current agri-environment reforms). Finally, the assessment points to the need to prioritise the designation of large contiguous areas for nature conservation, allowing the inclusion of such buffer zones. By contrast, designating fragmented or linear conservation sites places them at greater risk due to the increased fraction that represents edges vulnerable to ammonia.

Introduction

Ammonia emissions are an increasingly recognised threat to the biodiversity of natural and semi-natural habitats. The extra nitrogen (N) provided by ammonia (NH_3) deposition leads to changes in species competitiveness resulting in altered species composition of particular relevance for the integrity of many statutory designated habitats (Sutton *et al.*, 1993; Fangmeier *et al.*, 1994; Bobbink *et al.*, 2003;). Emissions of NH_3 arise primarily from livestock farming and therefore occur in the rural environment, often close to areas of nature conservation interest. For this reason, there are very large local gradients in NH_3 concentrations and deposition, and the worst problems occur where a large intensive livestock farm is located close (e.g., < 2 km) to an area of nature conservation value (Dragosits *et al.*, 2002). This "near source" problem is additional to the "long range" air pollution problem, where NH_3 emissions are dispersed hundreds of miles and deposited mainly in precipitation. Technical methods are available to reduce ammonia emissions, but many of them are expensive to farmers and have only limited effectiveness (e.g., Cowell and ApSimon 1998). As a result there is a need to look at complementary measures that can help protect natural habitats. Trees can play a key role as additional means to help mitigate the effects of atmospheric ammonia (Theobald *et al.,* 2001). The rates of ammonia deposition to woodland are larger than to other vegetation surfaces, so the existence of tree belts around farms can help recapture ammonia emissions. The rough surface of trees also helps to generate turbulence to disperse the ammonia, reducing deposition to sites immediately beyond the trees. In addition, the sheltering effect of trees can reduce emissions, while keeping animals under trees is also expected to reduce emissions substantially (Theobald *et al.*, 2004).

This paper summarises current thinking on NH_3 recapture and investigates the possibility of novel landscape-level abatement measures. It is shown that tree belts need to be wide enough to capture significant ammonia, but that they can have significant benefits at costs comparable or better than many conventional abatement techniques. The approach is by no means a panacea, but it could make an important contribution, particularly in the context of future agri-environment reform and for the protection of nature conservation sites.

National assessment of ammonia sources, sinks and mitigation

Until now, most effort has been placed in quantifying ammonia emission fluxes and investigating abatement strategies at the national scale. The Gothenburg Protocol of the United Nations Economic Commission for Europe (UNECE) and the EU National Emissions Ceilings Directive commit the UK to a national target for 2010 of 297 kt NH_3 year^{-1}. This represents a reduction of 11% from the official estimate of emissions for 1990 of 333 kt NH_3 yr^{-1}, and of 7% from the 320 kt NH_3 yr^{-1} estimated for 2000 (Defra 2002). These changes will, however, be insufficient to protect most UK ecosystems from the effects of atmospheric ammonia. Overall, 59% of UK ecosystems (by area for 1999-2001) have been estimated to receive atmospheric N deposition that is in excess of the ‘critical load’ for nitrogen eutrophication, so that biological and ecological changes due to ammonia are expected for much of the country. The situation is even worse for woodland, with critical loads for N exceeded for between 92% and 98% of UK woodlands (depending on woodland type). Based on the Gothenburg/NECD emission ceilings for 2010, the figures are estimated to be 49% for all UK ecosystems and between 80% and 96% for woodlands (Hall *et al.*, 2004).

It is important to consider not just these average estimates, but also the spatial distribution of emissions, deposition and critical loads exceedance. Such estimates are made with a combination of models (see e.g., NEGTAP, 2001; Hall *et al.*, 2004). Figure 1 compares the national distribution of atmospheric N deposition, including both reduced and oxidised nitrogen, according to the NEGTAP approach with the critical loads exceedance for nutrient nitrogen effects on this habitat. As woodland/forest is aerodynamically rough and receives little mineral fertilisation, it is an efficient sink of ammonia, so that these rates of deposition are larger than for other vegetation types. The high spatial variability is striking, and reflects the different source/sink areas of ammonia, as well as high wet deposition in hill areas. The exceedances represent the largest values for any land cover type, and imply substantial effects of N deposition on woodlands across the UK. The clearest effects are likely to be changes in woodland ground-flora species composition (e.g., Pitcairn *et al.*, 2002; Bobbink *et al.*, 2003), while tree growth and carbon storage may also respond to the additional nitrogen.

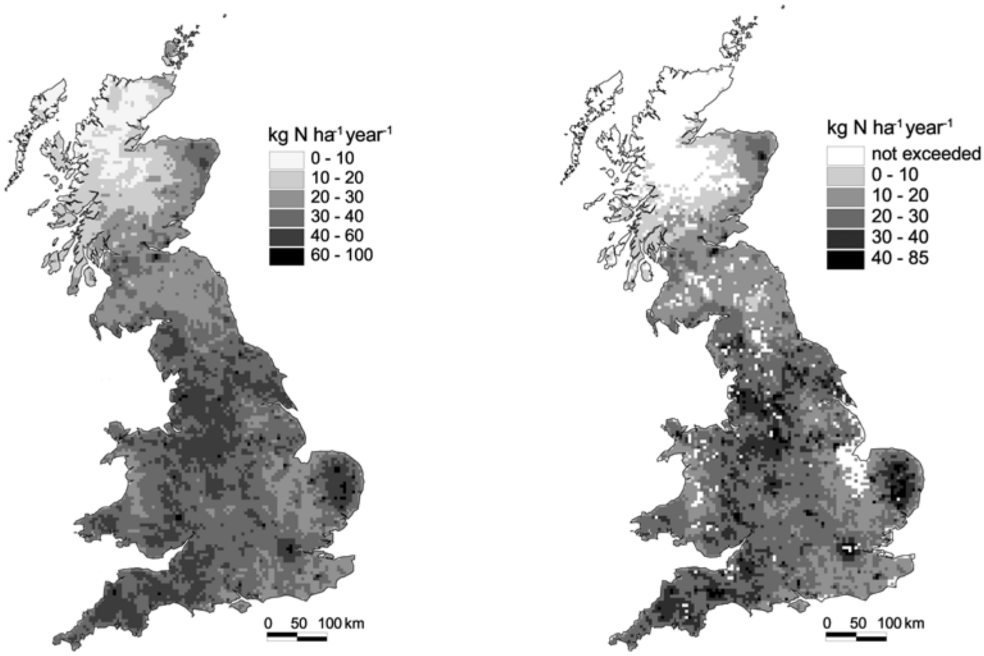

Figure 1. Estimated atmospheric nitrogen deposition and critical loads exceedance for nutrient nitrogen effects for woodlands/forest across Great Britain (estimates for 1995-1997).

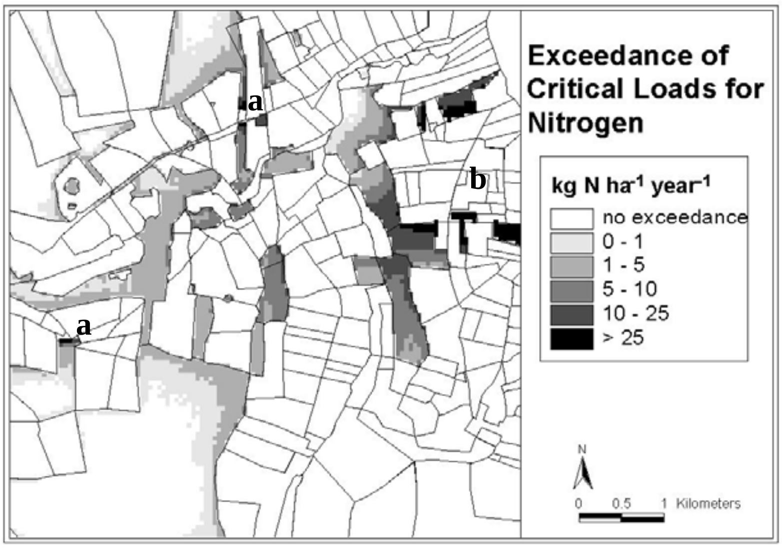

Figure 2. Exceedance of the critical load for nutrient N on woodlands and semi-natural vegetation for the modelled landscape of Ambridge in middle England (from Dragosits *et al.*, 2002). Farms are located at a. (small mixed beef farms) and b. (large poultry farm).

Landscape level variability in atmospheric N deposition and impacts

The national estimates of atmospheric N deposition are provided on a 5 km grid. These may be used directly for initial screening exercises, and are available through the UK Air Pollution Information System (APIS) (www.apis.ceh.ac.uk). It is, however, recognised that there is substantial sub-grid variability. This is an issue for NH_3 in agricultural areas, since sensitive ecosystems often occur in close spatial relationship to NH_3 sources (animal houses, manured and fertilised fields etc.) (Sutton *et al.*, 2003). Conducting a detailed assessment of the local variability of atmospheric N emissions and deposition is a significant task, but is very useful to investigate the spatial interactions between sources and sinks. Such an assessment has been made by Dragosits *et al.* (2002) for a rural landscape of 5 km x 5 km. For reasons of confidentiality, the location is referred to as “Ambridge”, an unspecified location in middle England. Figure 2 shows the spatial pattern of critical loads exceedance for N deposition in the Ambridge study area. As critical loads do not apply for agricultural fields and farms, these areas are left white. The farm sources cause major gradients in critical loads exceedance for woodlands and other semi-natural vegetation, both adjacent to the farms and the fertilised agricultural fields. While Figure 1 may not show exceedance at 5 km resolution for this square, Figure 2 shows that localised exceedances can be extremely large.

Spatial prioritisation of ammonia abatement

The current national policies are limited for several reasons. Firstly, as indicated, the anticipated emission reductions will not be sufficient to avoid exceedance of the critical loads, according to the national assessment. Secondly, local scale variability in deposition indicates even more extreme “hot spots” of nitrogen deposition, for which a conceivable 10-20% reduction in emissions would be insufficient to avoid effects. Thirdly, the national emissions ceilings approach does not consider which ecosystems should be protected in which locations of the country. This last point is important, since, if it is accepted that not all ecosystems can be protected, then there is a need to prioritise which areas should be protected. For example, it may be agreed that it is of higher priority to protect designated nature areas (e.g., Sites of Special Scientific Iinterest, SSSIs; candidate Special Areas of Conservation, cSACs) than other ecosystems. If this is agreed, it paves the way to explore novel methods of spatial planning as a complementary approach to reducing the environmental impacts of ammonia. Existing woodlands or new plantings can play an important role in such strategies by acting as buffer zones to capture and disperse ammonia.

The multiple benefits of trees for ammonia mitigation

Trees have several benefits to help mitigate the environmental impacts of atmospheric ammonia. These can be summarised as four distinct roles:

1. Ammonia emissions from many sources are a function of wind speed. *Trees provide shelter from wind*, potentially to reducing emissions (e.g., naturally ventilated buildings).
2. Trees capture ammonia more efficiently than other vegetation. Therefore, planting trees around animal buildings or fields can *recapture a fraction of the ammonia on the farm*, reducing the amount that is deposited to more sensitive ecosystems further afield.
3. Trees represent a rough surface that encourages downwind dispersion. The *additional dilution of emissions leads to lower ammonia concentrations immediately downwind*, which can be of benefit for nearby nature areas.
4. Ammonia emissions per kg N excreted are smaller for animals kept outdoors than for housed animals. In addition, where stock is kept under trees, *overlaying vegetation is expected to recapture a substantial amount of any emitted ammonia*.

It is important to emphasise that trees are not a panacea for ammonia abatement: there are clear limitations. For example, the amount that is recaptured by trees down-wind of farm buildings may be <10%, while a similar additional 10-20% nearby may result from the dispersion effect. It is important to recognise that explicit design of farm woodlands to recapture and disperse ammonia is important to maximise the recapture. Effects of wind sheltering may be significant, e.g., 20-30% reduction in emissions (Theobald *et al.*, 2004), but these require further analysis in relation to interactions with ground surface temperature.

Finally, the keeping of stock under trees represents an ancient practice for the cheap provision of both food and shelter. Obviously, there are practical limitations regarding the number of stock and the protection of viable woodland, but the approach may be extremely attractive for niche markets, such as “woodland chicken” (www.faifarms.co.uk) or even “pannage pork”.

As part of the AMBER project, Theobald *et al.* (2001; 2004) estimated the recapture of ammonia by a woodland downwind of a controlled field release of ammonia. Based on the woodland in question they also applied a new Lagrangian stochastic particle dispersion model (Loubet, 2000) to analyse the advective recapture within the woodland. They found that the woodland used for the experiment did not have the most optimal design, having a rather open under-story for its full width, which allowed ammonia to pass under the tree canopy. It was identified that an improved woodland design would be to ensure an open canopy under-story immediately adjacent to the source, but a dense canopy under-story at the down-wind edge, to ensure that the air is forced through the main tree canopy. While further work is clearly necessary to optimise such woodland design to maximise ammonia recapture, Figure 3 demonstrates the effect of width of the tree belt on ammonia recapture. This shows that a wider tree belt is estimated to capture substantially more ammonia. For a strip of woodland 15 m wide (with a 2 m high NH_3 source and 10 m high trees starting 5 m downwind of the source of the same canopy structure as in the experiment), 2.1% of the NH_3 was recaptured. By contrast, for a 60 m wide belt of trees the estimate was 7.1% recapture. This shows that a simple single row of trees will be insufficient to achieve substantial recapture, although the absolute values of the percentages might be increased by improved design of the tree belt.

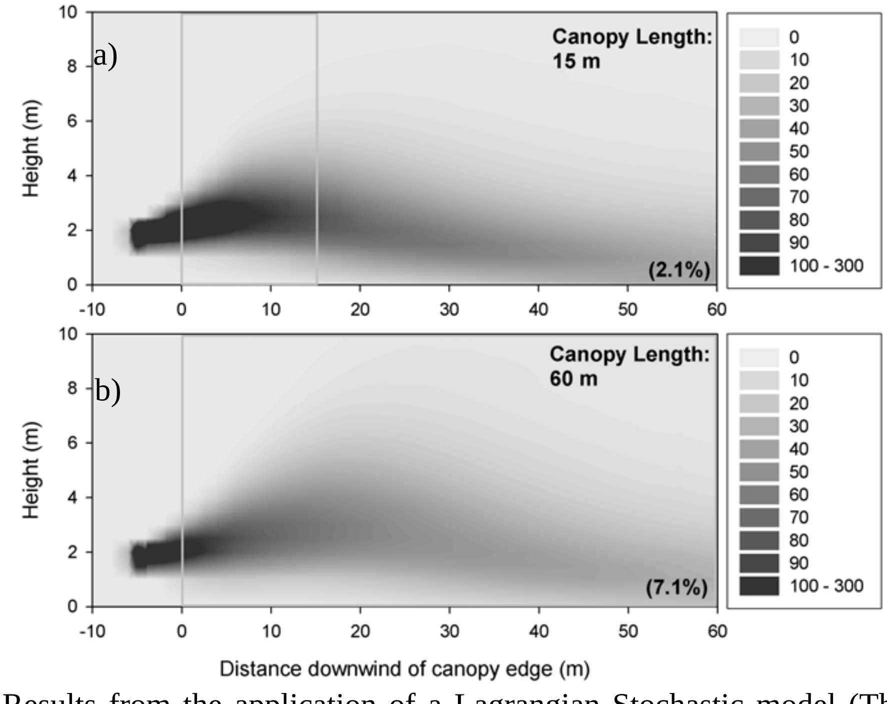

Figure 3. Results from the application of a Lagrangian Stochastic model (Theobald *et al.* 2004) to simulate the dispersion of ammonia in the canopy of an experimental woodland site. a. 15 m wide belt of trees; a. 60 m wide belt of trees. Units of shading: ug m^{-3} NH_3.

Landscape scenarios for ammonia abatement

The combined effects of recapture and increased atmospheric dispersion due to trees can be accounted for in the atmospheric dispersion modelling approach of Dragosits *et al.* (2002) for ‘Ambridge’. This assessment was made using the LADD (Local Ammonia Dispersion and Deposition) model, which includes the roughness effects and NH_3 affinities of different vegetation types in a simple way. By contrast, the effects of wind sheltering on NH_3 emissions or benefits of keeping stock under trees cannot currently be estimated in this model. The example of 'Ambridge' provides a starting point for the consideration of "what if" scenarios of landscape management for ammonia abatement. Two examples are considered here: a) the planting of woodland around sources of ammonia emissions (a large and a small livestock farm) and b) the planting of woodland around an area sensitive to ammonia deposition (a large and a small area for nature conservation). For the scenarios here, the intensive poultry farm in Figure 2 was 'moved' to the west ~2.5 km, while selected areas of woodland /semi-natural land were denoted as hypothetical SACs (hSAC). Figures 4a and 4b show the difference in deposition with and without a 50 m belt of trees round the farms and nature reserves, respectively for part of the study area.

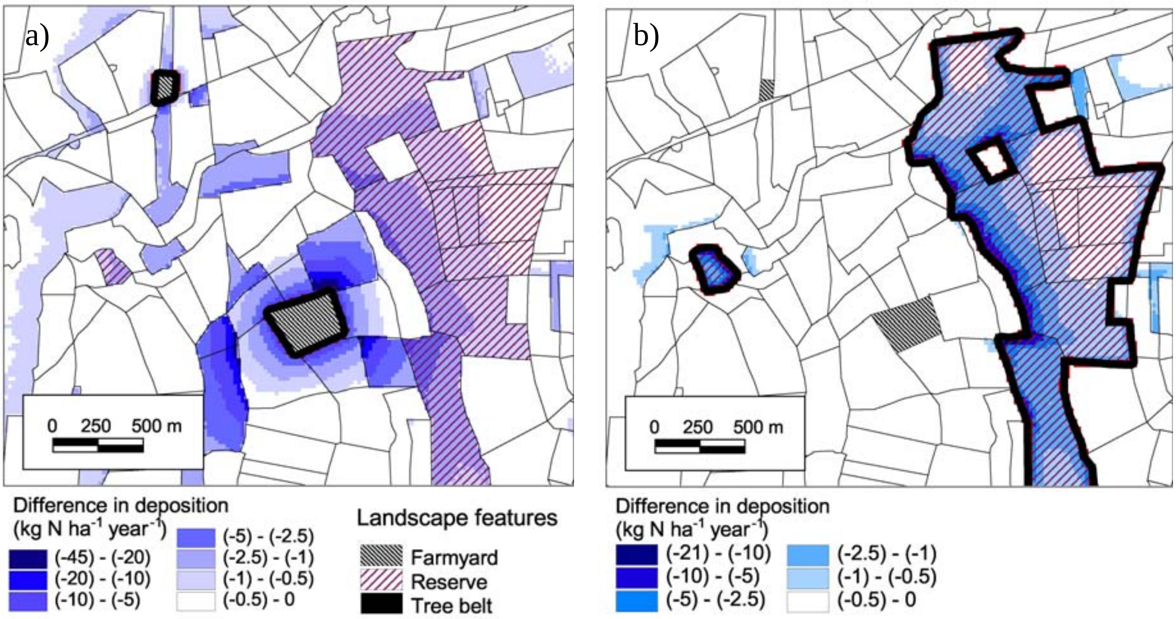

Figure 4. Effect of two scenarios of landscape planning using trees to reduce the impacts ammonia deposition on two hypothetical Special Areas of Conservation (hSAC). Reductions in deposition in neighbouring areas resulting from planting 50 m wide belts of trees a) around two farms, and b) around two hSACs.

The increased deposition to trees "planted" around the farm buildings (Figure 4a), and the increased dispersion leads to a reduction in deposition that is largest near the farms (beyond the planted trees) and extends into the hSACs. The estimated reduction in deposition in the hSACs is up to 5 kg N ha^{-1} yr^{-1}. If the critical load for the nature reserves were 10-15 kg N ha^{-1} yr^{-1}, this would represent a reduction up to 33-50% of the critical load. Substantial benefits are also seen in other nearby semi-natural and woodland areas, apart from the hSACs. The scenario of planting trees around the two hSACs produces benefits that are targeted almost exclusively on the hSACs themselves (Figure 4b). The benefits are largest at the edges of the hSACs nearest the largest sources of NH_3, with values up to 10 kg N ha^{-1} yr^{-1}, or 66-100% of the same critical load assumed above. This second scenario provides increased benefits for the small hSAC compared with the first scenario, since, by nature of its small size, all of the reserve is close to the trees. While these represent significant reductions in deposition in relation to the critical load, it is important to recognise that current deposition may be substantially larger above the critical load. Hence, while such measures will help, they may need to form part of a package of measures to protect the hSACs.

Discussion and conclusions

The UK analysis of critical loads exceedance for woodlands provides startling and worrying results: around 90% of all woodlands in the UK are estimated to receive deposition in excess of the critical load. This indicates that woodland flowers and other ground flora are being substantially affected by atmospheric nitrogen deposition, with the effects to a large extent being a result of ammonia emissions. Current UK policies, which aim at a ~10% reduction in ammonia emissions by 2010, are not sufficient to avoid this threat. This means, that we need to prioritise what should be protected (to maximise the benefits in proportion to the costs of any abatement strategy) and that imaginative approaches are needed to find complementary methods for mitigating the effects of atmospheric ammonia. Trees can play an important role in landscape planning to protect priority from N deposition. In this case, trees may be planted 'sacrificially' around farms or statutory conservation sites to do the job of capturing and dispersing ammonia. Effects of N deposition are therefore expected in such woodlands, in return for a reduction in effects on priority nature conservation areas.

It is important to note the constraints in this approach to ammonia abatement. Firstly, the undesirable effects on such woodlands need to be accepted (e.g., changes in woodland ground flora, increases in emissions of oxidised nitrogen). Other possible effects on protected sites also need to be considered, such as on water levels. By contrast, these woodlands may provide additional benefits, such as for visual screening, recreation, cover for wildlife and shelter for stock. The benefits of ammonia abatement could also be counted towards the scoring of woodland grant scheme proposals (Theobald *et al.*, 2004). Such benefits complement the use of woodlands in urban air quality planning, where they may be used to reduce particulate matter (PM_{10}) concentrations (Bealey *et al.*, 2004). The planting of trees is of particular interest in relation to current agri-environment reforms. Agricultural grants are becoming increasingly decoupled from production and linked more closely to environmental protection. Hence land around livestock farm buildings or nature reserves, which is currently grassland or arable land, might more easily be converted to farm woodland. The challenge is to ensure that the ammonia issues are considered as part of these agri-environment reforms.

Finally, the landscape analysis points to the benefits of designating statutory nature areas as large contiguous blocks, rather than isolated fragments or linear features. The habitats of small or linear conservation sites are at higher risk from ammonia deposition from adjacent agricultural activities, due to the increased fraction of the area that represents edges. Hence, by prioritising the protection of larger areas (over smaller fragments) it is more likely that there is space available for "buffer zones", while areas at the centre of the reserve are an increased distance away from the nearest ammonia sources. Such buffer zones could either be outside or inside the boundary of designated area (e.g., SSSI or SAC). The former might consist of avoiding use of manures on adjacent fields, or planting adjacent fields with woodland. Placing buffer zones *in* the designated areas would put less pressure on adjacent land managers, but would require new regulatory approaches, e.g., to SACs, where "significant adverse effects" would be considered as acceptable within the buffer zone. Such strategies point to the benefits of retaining existing woodland on the boundaries of conservation sites, even though a site may be designated for another habitat. For example, a site may be designated for its heathland, but retention of an existing belt of trees around the site would be useful to reduce the impacts of ammonia. In an agricultural region, this may be preferable to restoring the entire area of the site to heathland. Although restoration of woodland to heathland would increase the heathland extent, this would place the existing heath under increased threat from ammonia.

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