The effects of agricultural practices on the nitrate concentrations in the surface water domestic supply sources of western Europe

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ABSTRACT During the last thirty years or so, nitrate concentrations in the surface waters of most western European countries have been rising steadily. Although these increases can be attributed to many factors, it is generally agreed that the major contributor has been the intensification in agricultural practices, particularly the massive increase in the use of inorganic fertilizers, that has been a feature of this period. In some areas, concentrations in surface water domestic supply sources exceed intermittently, or continuously, the World Health Organization limit for nitrate in potable water. Estimating the amount of leaching losses from agricultural land is difficult because it is subject to a number of factors including soil type, crop grown, rate and timing of fertilizers and climate. Also, predicting future losses is complicated by future plans within the Common Agricultural Policy of the EEC bearing in mind the overproduction that is currently being achieved.

Les effets des pratiques agricoles sur les concentrations des nitrates dans les sources de l'alimentation en eau de surface pour utilisation domestique Europe occidentale

RÉSUMÉ Pendant les trente ans qui viennent de s'écouler, les concentrations des nitrates dans les eaux de surface dans la plupart des pays de l'Europe occidentale ont augmenté de façon régulière. Bien qu'on puisse imputer ces accroissements à bien des facteurs, l'opinion universelle est que le facteur principal réside dans l'intensification des pratiques agricoles, surtout en ce qui concerne l'augmentation massive de l'utilisation des engrais inorganiques, ce qui a été fort caractéristique pendant cette période. Dans quelques régions les concentrations dans les sources de l'approvisionnement en eau de surface pour utilisation domestique excèdent, ou par intervalle ou de façon continue, la limite imposée par "World Health Organization" pour le nitrate dans l'eau potable. L'estimation de la quantité de pertes par lessivage des terres arables est bien difficile, car il s'agit de plusieurs facteurs qui comprennent le type du sol, le type de culture, le taux et la distribution des engrais et le climat. Du reste, la prévision des pertes futures est rendue plus complexe par les projets proposés selon la
The development of civilizations is usually accompanied by increased demands for water and food. As the exploitation, and integration, of water resources has become more sophisticated to meet the challenge of rising demand, so agricultural practices have intensified to increase food production. In Europe, as elsewhere, the impact of this intensification and, in particular, the very rapid growth in the use of inorganic fertilizers, on water quality initially attracted little attention. However, as the health and environmental implications became clearer, research studies and water quality monitoring programmes began to clarify and assist in the understanding of the complex processes involved.

The public water supply in the industrialized countries of western Europe is derived from a combination of surface waters (reservoirs and rivers), spring waters and groundwaters. On a local scale, the type of source utilized will rely on a combination of the geological, hydrological and topographical conditions and the percentage of surface water abstraction may vary from 70% in Spain to less than 1% in Denmark. Where a source is connected to a domestic distribution network, the quality of the water must conform to certain standards. One of the determinands that has to conform is the concentration of nitrogen in its nitrate form. This follows evidence that excessive nitrate in drinking water is the cause of methaemoglobinaemia in young babies and, more recently, that there could be a link with gastric cancer, though evidence of the latter is not conclusive. Most western European countries adopt the World Health Organization standard for drinking water which specifies a recommended limit of $11.3 \text{ mg}^{-1} \text{ NO}_3^-$ with an acceptable limit of $22.6 \text{ mg}^{-1} \text{ NO}_3^-$. More recently the European Economic Community issued a directive that effectively halved these limits, but its adoption by the various countries is still a matter of debate.

During the last 30 years or so, a steady increase has been observed in the nitrate concentration in many water supply sources. Large differences do occur from country to country and for different regions within individual countries. In some instances, the concentrations are stable whilst, in others, the concentrations have risen to such an extent that the water supply source has had to be discontinued.

Temporal and spatial variations in the nitrate content of surface waters reflect the interaction between climate, soils, land use (both current and historical) and other factors; as a consequence, the vulnerability of communities to nitrate pollution varies substantially. The design of suitable strategies to alleviate the problems associated with high-nitrate waters needs to take full account of this geographical variation, and the processes contributing to it, in order that practical control programmes can be successfully introduced.

In general, the highest concentrations are found in urban areas.

*All concentrations in this paper are expressed in $\text{ mg} \text{ l}^{-1} \text{ NO}_3^-$. 
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which are subject to point sources of pollution from sewage, industrial effluents, combustion products etc., and in areas under intensive agriculture where point sources of pollution from accidental spillage of silage liquor and slurries, for example, are augmented by non-point sources as a result of increased fertilizer usage. The latter category is generally thought to be the most polluting and is also the most difficult to legislate against.

Nitrate data are presented in this paper which illustrate these rising concentrations, their spatial variability and their variation with land use. In particular, the intensification in agricultural productivity is identified as the principal reason for these rising trends. The processes affecting nitrate leaching from agricultural land and possible ways of reducing these losses are discussed.

Most of the data presented are from the United Kingdom, though recent international workshops and symposia suggest that the situation is similar throughout much of western Europe.

HISTORICAL TRENDS IN NITRATE CONCENTRATIONS

Although records exist testifying to the polluting effect on water courses of high application rates of manure over a century ago (Voelcker & Frankland, 1875), extended time series of nitrate concentrations in rivers and streams are uncommon throughout much of Europe. It is only relatively recently, as a result of the growing concern in relation to a range of potential pollutants, including nitrate, that nationwide water quality monitoring schemes have been established. However, sufficient historical data have been assembled to demonstrate clearly that increasing nitrate concentrations in surface waters have been a major feature of the changing quality conditions of European rivers over the past 20 or 30 years. Large spatial variations in the rate of nitrate increase have been observed. In addition, many nitrate time series are characterized by substantial seasonal and year on year variability, with periods of rapid increases in nitrate concentrations separated by periods of relative stability. Such factors make the assessment of trends a difficult exercise, particularly when records are short and when much of the recent data have been collected during a period of considerable climatic volatility (Morris & Marsh, 1985); climate and land use practices interact in a complex manner to produce greater or lesser volumes of nitrate for leaching into surface waters. For these, and other, reasons, the assessment of a meaningful average rate of increase in nitrate concentrations, under European conditions, must remain somewhat speculative. For the United Kingdom, however, the average rate of increase was found to be about 0.15 mg l⁻¹ (NO₃-N) per year over the period 1960-1980 (STACWQ, 1983).

Figure 1 illustrates annual mean nitrate concentrations for four rivers in England. Generally, the annual means have been derived from the results of weekly or fortnightly sampling. Whilst each series exhibits a positive trend and a greater degree of variability over the last 15 years, land use contrasts between catchments results in large differences, both in the level of nitrate pollution and in its rate of increase. The River Tees in northern England drains
mainly poor upland pasture and shows little increase in nitrate concentrations during the last 25 years. The Stour, on the other hand, which drains a catchment given over to intensively cultivated arable land, has exhibited a rising trend since records started in 1937 and, currently, the annual mean concentration is approaching the WHO recommended limit. The most rapid increases in nitrate concentrations have occurred in catchments of this type, characterized by low rainfall and arable farming practices. Conversely, far more stable conditions obtain in the upland catchments where rainfall is plentiful and rough grazing and forestry are the primary agricultural activities; in such catchments nitrate concentrations remain low, often less than 2 mg l\(^{-1}\) NO\(_3\)N (Marsh, 1980). Whilst other factors, particularly population density, are important in certain catchments, the association between the trend in nitrate concentrations and the quality of the land (and hence the farming practices adopted) is a compelling one.

![Graph showing trends in nitrate concentrations in four British rivers.](image)

FIG.1 Trends in nitrate concentrations in four British rivers.

The steep increases in nitrate concentrations in rivers draining the English lowlands are matched by similar rates in analogous catchments throughout western Europe. However the more important continental rivers have very much larger, and often more heterogeneous, catchments than are found in the UK. Major rivers such as the Rhine, the Danube and the Elbe have significantly lower nitrate concentrations, and less pronounced positive trends, than those shown in Fig.1. Figure 2 illustrates the annual average nitrate concentrations in the River Rhine at Lobith, close to the Netherlands border, (Dykzeul, 1982). The trend up to 1977, and the subsequent more muted increase, are familiar features but, overall, the year on year change is only of the order of 0.15 mg l\(^{-1}\) NO\(_3\)N. In addition, the seasonal variation, though very regular, ranges through 3-5 mg l\(^{-1}\) NO\(_3\)N only; in lowland England, winter concentrations will often exceed the summer average by a factor of three. The relative stability displayed by nitrate concentrations on the Rhine reflects
its size and, in particular, the massive dilution afforded by the meltwater component which constitutes a major proportion of the river flow in the late spring and early summer. Above Basle, nitrate contamination is minimal. Downstream, runoff from the land and sewage effluent contributions result in a steady increase in river-borne nitrate. The sewage effluent component has assumed a particular importance since the 1960's as an increasing proportion of the catchment population has been connected to sewerage systems draining to the Rhine. Nonetheless, the clear seasonality displayed by the nitrate concentrations is indicative of the greater importance of land runoff in influencing concentrations throughout much of the middle and lower reaches of the Rhine.

In many regions of Europe, groundwaters make a substantial contribution to river discharge, particularly during the summer and early autumn when surface runoff may be limited or absent. Nitrate contamination of aquifers, and in the overlying unsaturated zones, has been widely reported in recent years. As a consequence, the baseflow components of many rivers, especially those draining arable catchments, are now richer in nitrates. The River Frome (see Fig.3) is a typical chalk catchment in southern England, given over predominantly to pasture; a steady increase in annual mean nitrate concentrations has been recorded over the last 20 years. Figure 3 also illustrates a longer time series for a spring in the fissured limestones of the Brie region in France. The steeper rate of increase in nitrate concentrations since the 1960's may be attributed to the more intensive agriculture - the Brie region is a major producer of cereal crops - and the fissured nature of the aquifer which allows the nitrate to reach the water table relatively quickly.

CURRENT SITUATION

In Great Britain data collected as part of the Department of the Environment's Harmonized Monitoring Programme provide a comprehensive picture of nitrate contamination of rivers. Water quality sampling frequencies are typically in the range 12-24 per year, allowing the annual mean nitrate concentrations to be established with reasonable confidence. Figure 4 illustrates the average concentration for some
235 sites over the period 1979–1984. Mean concentrations range from below 0.5 mg l⁻¹ NO₃N in the Scottish Highlands and the Welsh mountains to greater than 10 mg l⁻¹ NO₃N for some rivers in central and southeastern England. The higher average concentrations are normally found in rivers where an obvious seasonal cycle may be recognized with peak concentrations occurring in the autumn and the winter (Fig.5). This seasonality has intensified as diffuse sources have assumed a greater importance relative to point sources of pollution (agricultural, industrial and, particularly, domestic) which were, in the past, the dominant sources of nitrate contamination. Over the last decade, nitrate concentrations have exceeded 11.3 mg l⁻¹ NO₃N at a third of the monitoring sites featured on Fig.4 and, in the Anglian Water Authority area, average nitrate concentrations are often close to this limit with peak concentrations (often recorded following the 1976/1977 drought) breaching the 22.6 mg l⁻¹ limit. These elevated concentrations are commonly associated with low rainfall and intensive agricultural practices although relatively high population densities are also important in some catchments.

Conversely, regions of high relief and rainfall tend to be characterized by very modest nitrate contamination. The influence of changing topography and land use on nitrate concentrations is illustrated in Fig.6 which shows land type and mean concentrations for the years 1983–1986 for points within the Wye catchment in Wales. The River Wye, which is 250 km long, drains a predominantly rural catchment which, in 1970, was composed of 37% permanent grass, 20% tillage, 15% rough grazing, 14% temporary grass and 9% forestry. All the rough grazing occurs at the head of the catchment, the land generally improves in a downstream direction and, as a consequence, the agriculture becomes increasingly intensive. Annual rainfall
FIG. 4 Mean concentrations of nitrate in river waters for the years 1979-1984.
rates vary from about 2500 mm at the head of the catchment to about 800 mm at the outfall. This, together with differences in evaporative rates, results in streamflow losses per unit area being approximately seven times greater in the upper than in the lower reaches. Mean nitrate concentrations reflect the changes of land use, being very low, less than 0.5 mg l\(^{-1}\) NO\(_3\)N, at the top end and increasing gradually downstream as the agriculture intensifies. Although some of the lowland tributaries have concentrations above 10 mg l\(^{-1}\), the dilution effect of the large runoff high quality upland water ensures that concentrations in the main river remain low.

![Graph showing nitrate concentrations in the River Stour at Langham.](image)

**FIG. 5** Nitrate concentrations in the River Stour at Langham.

On the European mainland, the same general contrasts in the spatial variation in nitrate concentrations may be recognized. The wet mountain and pasture regions of Scandinavia and the Alps provide substantial volumes of almost nitrate-free runoff whereas much more significant contamination may be found in the north European plain and in the Low Countries. However, any direct comparison with the UK is complicated by the somewhat different drainage pattern on the continent where total outflows from a country may be dominated by the runoff from a few major rivers. These rivers, sustained by large volumes of low nitrate water from the headwaters, often exhibit considerably lower concentrations than those for small tributaries in the middle and lower parts of the catchment. Figure 7 shows the average nitrate concentration for a selection of water
quality monitoring sites in Germany (Anon, 1983). The emphasis on major rivers tends to underestimate the magnitude of the nitrate problem when, for instance, it is known that many of the streams draining the important vegetable and viticulture region of Baden-Württemberg carry water considerably richer in nitrate than the Rhine itself. Similarly, in the Netherlands where nitrate concentrations in the River Maas and the various distributaries of the Rhine seldom exceed 6 mg l⁻¹ NO₃⁻N significantly greater nitrate contamination, up to 18 mg l⁻¹ NO₃⁻N, has been widely detected in water courses draining the polder areas of the western and northern parts of the country, (Anon, 1986).

Any sound nitrate management strategy must rely on an understanding of the relationship between changes in nitrate inputs to a river system and the consequences in terms of variations in nitrate concentrations. The monitoring of small representative catchments will continue to play a crucial role in improving our knowledge of the processes involved. Examination of the mass transport of nitrate has helped establish the relative importance of different nitrate sources under differing climatological, hydrological and demographic conditions and under widely contrasting land-use conditions. Annual nitrate loads vary greatly from year to year, often

![Diagram of Land Classification](image)

**FIG. 6** Average 1983-1986 nitrate-N concentrations (mg l⁻¹) in the Wye basin.
showing a strong correlation with winter runoff volumes. Spatially however, a greater uniformity may be evident with rather more muted contrasts in average annual catchment yields than is displayed by mean annual average nitrate concentrations. This arises because very high runoff volumes in the rivers draining low nitrate areas tend to balance the more limited runoff which typifies the regions with the highest nitrate contamination. At the catchment scale, average annual loads throughout England and Wales typically range from 10 to 50 kg ha\(^{-1}\) with 20 to 30 kg ha\(^{-1}\) characteristic of much of the English lowlands (Rodda & Jones, 1983); much higher loads have been reported for small research basins and experimental plots. Taking England and Wales as a whole, land runoff has been estimated to contribute about 50% of the nitrate entering rivers and streams above their tidal limits; a comparable amount derives from sewage effluent (Marsh, 1980). In the Federal Republic of Germany the relative proportion of nitrate derived from land runoff has been
assessed to be somewhat higher. Significantly, the land runoff component is normally the dominant contribution to river-borne nitrate in those water courses experiencing the more rapid increases in nitrate contamination.

A measure of the vulnerability of water courses throughout Europe to further increases in the nitrate content of runoff from the land may be gauged by considering the implication of a relatively modest rise of 5 kg ha\(^{-1}\) year\(^{-1}\) in the nitrate (as N) load reaching the rivers and streams. Average annual runoff over the greater part of the northern European plain, and throughout much of lowland England is less than 200 mm; for a number of important arable farming regions, below 100 mm is more typical. Thus only limited volumes of local river discharge will be available to dilute the additional nitrate load and as a consequence, concentrations may be expected to rise by 2-4 mg l\(^{-1}\) NO\(_3\)N (on average) in rivers draining catchments in the low rainfall areas. Such an increase would result in the widespread exceedance of the WHO limit particularly during the October-March period.

TRENDS IN AGRICULTURAL PRACTICES

The increase in nitrate losses from agricultural land is a reflection of the intensification in agricultural practices that has occurred since the 1939-1945 war. During this time, there was a marked increase in the amount of arable land at the expense of permanent grassland in many countries of western Europe, though since then the rate of conversion has been very low. Studies have shown (see, for example, Reinhorn & Avnimelech (1974), Cameron & Wild (1984), that substantial losses of soil nitrogen can occur as a result of ploughing permanent grassland. However, whilst these losses do have an initial impact on nitrate concentrations, they are generally short-term, and it is the subsequent massive increase in fertilizer application rates, allied to the introduction of more intensive farming practices, to maximize crop yields that has had the biggest impact. Fertilizer usage in five European countries is shown in Fig.8 and shows, typically, a doubling in the last 20 years. Obviously, annual rates of application will depend on the extent of agricultural land in the individual countries, though the data for 1981 suggest that, for the countries shown in Fig.8, the rates are highest in the Netherlands (237 kg ha\(^{-1}\) average) and lowest in France (70 kg ha\(^{-1}\) average). Conversely, the greatest increase in the application rates for the years 1961-1981 have been found in France with the lowest in the Netherlands.

Agricultural soil contains substantial reserves of nitrogen, the exact amount depending on the type, climate, land use and previous management. Most of this nitrogen is in the organic, immobilized form, unavailable for plant uptake and loss by leaching to surface and ground waters. A relatively small amount of this organic nitrogen is mineralized into, mainly, the nitrate form during the growing season where it is available for either crop uptake, leaching or, in some instances, gaseous loss. The store of organic nitrogen within the soil is replenished during the autumn as plant residues die. There is also a natural input to the soil store in the form of
dry and wet precipitation.

The extent of mineralization depends on a number of soil properties including temperature, acidity, water content and, particularly, degree of aeration. Within each soil type, climate and land use situation, there will be a typical range of mineralization rates and hence potential leaching losses. This range will be large, reflecting the large quantities of potentially mineralizable organic matter and the number of contributory factors. Some of the smaller rates occur under undisturbed conditions such as permanent pasture where relatively anaerobic soil conditions occur. This, together with the permanent vegetation cover and efficient uptake of any available soil nitrogen by the root mat, ensures that annual leaching losses under this land use are very small indeed, often less than 1 kg ha\(^{-1}\). In fact, permanent grassland is a net accumulator of soil organic nitrogen. This is also the case when fertilizer is applied though, as rates increase, higher leaching losses will become evident as the grass is unable to utilize the amount of nitrogen, and other nutrients, supplied. Increased losses will also occur following ill-timed fertilizer applications. This was observed in a 170 ha mainly grassland catchment in Buckinghamshire, UK, when a fertilizer

![FIG. 8 Fertilizer usage in western Europe.](image_url)
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Application during a wet spring in 1983 resulted in very high nitrate concentrations in the stream, the peak value being approximately ten times the WHO recommended limit (Roberts, 1986). It was calculated that 40 kg ha\(^{-1}\) of nitrogen was lost to the stream during that spring compared with an application rate of 90 kg ha\(^{-1}\). In general, though, grassland if managed correctly, is a very efficient utilizer of nitrogen with few leaching losses.

Following the ploughing of permanent grassland, much of the mineral nitrogen produced will be available for leaching from the soil zone as the land lies fallow. The same will be the case under arable cultivation when harvesting and ploughing during the autumn will cause a similar effect. This is the primary reason for the seasonality observed in streamflow nitrate-N concentrations in rural areas (Fig. 5). The amount of nitrogen leached depends on the time that the land was under undisturbed conditions prior to ploughing, ranging from a loss of 30 kg ha\(^{-1}\) from a one year old pasture to 260 kg ha\(^{-1}\) from a four or more year old pasture, (Young et al., 1976). Although most of these losses occur in the first year, the effect continues for some years.

Of a more long-term nature, however, will be the leaching losses as a result of the high fertilizer rates applied to maximise the yields of arable crops. Rates of fertilizer utilization by growing crops have been estimated from a number of field trials at Rothamsted and Woburn, UK (Johnston, 1976) and by the use of \textsuperscript{15}N labelled fertilizers (Dowdell, 1982). From these studies, a figure of approximately 50% utilization for a wide variety of crops receiving different rates of nitrogenous fertilizer has been deduced. A large range of variation occurs, however, reflecting the number of controlling factors including crop type, climatic conditions, rate and timing of additions and availability of soil nitrogen as a result of previous cropping practices and mineralization. Again, the fate of the remaining 50% of the applied fertilizer will depend on the conditions, being divided between soil nitrogen enhancement, gaseous loss and leaching. The leaching losses under certain conditions may be as large as, for example, the estimated range of 30-50 kg ha\(^{-1}\)yr\(^{-1}\) in East Yorkshire, UK, by Lawrence et al. (1983). As well as being potential pollutants to potable water supplies, they also constitute a monetary loss to the farming community. For example, the losses quoted for East Yorkshire above represent a loss to agriculture of £10-15 ha\(^{-1}\)yr\(^{-1}\) at current (1986) prices.

Legislating against nitrate pollution from non-point agricultural sources is much more difficult than from point sources. Whereas the origin of the latter can usually be identified without too much trouble and appropriate action taken, the former, because of its diffuse nature, cannot be so readily controlled. In some instances, sensitive water supply sources are protected by restricting the agricultural practices on the surrounding land either by purchase by the water authority or by the imposition of protection zones. More often than not, however, the protection of these sensitive sources is achieved through dialogue between the landowner and the water authority.

Following a growing realization of the polluting aspects of certain agricultural activities, a number of documents (see, for example, MAFF, 1985) have been published giving advice to farmers on
reducing water pollution. Much of this advice is directed towards reducing winter losses by growing winter cereals or a "catch-crop" following harvest to make use of mineralized nitrate. Advice given with regard to fertilizer usage include the avoidance of autumn seed bed nitrogen applications and the use of split applications for particularly high rates.

In the end, however, the agricultural practices employed will continue to be those that give the maximum yields and hence the maximum profits unless the landowners can be convinced of the advisability on economic grounds of replacing existing farming methods by newer ones which are more sympathetic to the environment. Financial incentives to encourage the adoption of less intensive farming practices have been introduced in some countries although not always with the primary intention of protecting water supply sources.

FUTURE TRENDS

Future trends in nitrate concentrations in surface waters depend on a combination of changes in agricultural policies, demographic changes and advances in sewage treatment techniques. For the former, predicting future trends is complicated by the possible impact of future changes in the Common Agricultural Policy of the European Economic Community. Increases in river-borne nitrate over the last quarter of a century have occurred against a background of the need to increase domestic food production. However, at present, large surpluses of many agricultural products are being produced within the EEC. Whether this will be allowed to continue and, if not, what steps are to be taken to reduce yields remains to be seen. In the UK, it is generally agreed within the agricultural community that nitrogen fertilizer applications to arable crops are at or about their optimum value for crop production and it is predicted that the usage of fertilizer N will increase by about one-half by the year 2000, a similar rate of increase to the last 20 years (Fig.8), most of the increase being applied to grassland (Gasser, 1982). Even then, the rates for the UK will be about the same as those being currently used in West Germany and Denmark and only about 50% of those currently being applied in the Netherlands (OECD, 1986).

Although, as indicated previously, grass is an efficient utilizer of applied fertilizer, increased applications from the current average of 110 kg ha$^{-1}$ year$^{-1}$ will, almost inevitably, lead to an increase in leaching losses. For example, research has shown that leaching losses from permanent grassland receiving 250 kg N ha$^{-1}$ are, on average, only 1.5% of the applied fertilizer, in the range 0.4-6.3 kg ha$^{-1}$ year$^{-1}$ (Barraclough et al., 1983). These, and other results, suggest that by careful management and timing of applications, leaching losses can be minimized. However, as demonstrated for a small clay catchment in the UK (Roberts, 1986), massive losses will occur under certain conditions.

Whilst overall nitrogen inputs increase, there must be an expectation that nitrate loads in rivers will also rise. In addition, the persistent nature of groundwater contamination implies
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that the nitrate contribution from baseflow will become increasingly important in many areas. An increase in leaching losses of 10 kg ha\(^{-1}\)year\(^{-1}\) will approximately double the nitrate concentrations throughout Europe; this serves to emphasize the need for a continuing dialogue between the water industry and agricultural interests to ensure that the available nitrogen is as effectively, and as fully, utilized as is practicable.

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