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Landscape fragmentation in Europe

Joint EEA-FOEN report

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Acknowledgements

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Foreword by EEA and FOEN directors

Landscapes are the setting for all human activities, providing a home to humans and all other life forms. Landscapes change constantly but in recent decades humans have often shaped them with little thought to the cumulative impacts and at a pace that is unprecedented. The value of landscapes is not yet fully reflected in decision-making on transport infrastructure and urban development. Considerations such as biodiversity and landscape quality are often marginalised.

One of the most important issues is fragmentation of landscapes by human activities and infrastructure — a major cause of the alarming decrease in many European wildlife populations. Fragmentation results in collisions with vehicles, prevents access to resources, facilitates the spread of invasive species, reduces habitat area and quality, and subdivides and isolates animal populations into smaller and more vulnerable fractions. Noise and pollution from traffic also threaten human and environmental well-being, and impair the scenic and recreational qualities of the landscape.

For the first time, this report presents the extent of landscape fragmentation across an entire continent using a scientifically sound method. It also reveals the most relevant driving forces behind fragmentation, demonstrating that varying factors are relevant in different parts of Europe. The picture it paints is worrying.

The extent of landscape fragmentation in many parts of Europe is already considerable. And proliferating urban development and transport infrastructure will increase the problems tremendously, particularly since many ecological effects of current fragmentation have yet to manifest fully.

In short, the current trend of steadily increasing landscape fragmentation contradicts the principle of sustainability. There is a clear and urgent need for action.

This report provides a foundation for environmental monitoring and protective measures for those landscapes that are not yet fragmented. It also makes it clear that fragmentation analysis must be integrated into transport and regional planning so that cumulative effects are considered more effectively in the future. One example of a successful policy implementation aiming at the reduction of fragmentation in the Swiss Alps is the so called 'Alpine Article' in the Swiss Federal constitution (art. 84) which limits the capacity of trans-alpine road transportation (*The capacity of the transit routes in the Alpine region must not be increased*) and demands a shift to railway transportation for goods.

This report is aimed at all those involved in traffic and regional planning in Europe, as well as interested members of the general public. The report is the result of fruitful collaboration between the Swiss Federal Office for the Environment (FOEN) and the European Environment Agency (EEA). Switzerland became a member of the EEA in 2006.

The success of this study raises hope that the threats to Europe's landscapes will become more widely understood and more effectively addressed for the benefit of future generations.

Professor Jacqueline McGlade, Executive Director, European Environment Agency, Copenhagen

Dr Bruno Oberle, Director, Federal Office for the Environment, Berne

Summary

Landscape fragmentation in Europe

Landscape fragmentation caused by transportation infrastructure and built-up areas has a number of ecological effects. It contributes significantly to the decline and loss of wildlife populations and to the increasing endangerment of species in Europe, for example through the dissection and isolation of populations, and affects the water regime and the recreational quality of landscapes. In spite of the planning concept of preserving large unfragmented areas, fragmentation has continued to increase during the last 20 years, and many more new transportation infrastructure projects are planned, in particular in eastern Europe, which will further increase the level of landscape fragmentation significantly. Therefore, data on the degree of landscape fragmentation are needed that are suitable for comparing different regions, especially in relation to different natural landscape types and different socioeconomic conditions. This report quantitatively investigates the degree of landscape fragmentation in 28 countries in Europe for the first time for three different fragmentation geometries at three levels. The three levels include countries, regions (NUTS-X, according to the Nomenclature of Statistical Territorial Units), and a grid of 1 km^2 cells (LEAC grid, which is used for Land and Ecosystem Accounting activities).

The report applies the method of 'effective mesh density' which quantifies the degree to which the possibilities for movement of wildlife in the landscape are interrupted by barriers. The effective mesh density values across the 28 investigated countries cover a large range, from low values in large parts of Scandinavia to very high values in western and central Europe. Many highly fragmented regions are located in Belgium, the Netherlands, Denmark, Germany, France, Poland and the Czech Republic. High fragmentation values are mostly found in the vicinity of large urban areas and along major transportation corridors. The lowest levels of fragmentation are usually associated with mountain ranges or remoteness. Fragmentation geometry B2 'Fragmentation of non-mountainous land areas' which includes highways up to class 4, railways and urban areas, is the most important fragmentation geometry, as it is suitable for comparing regions with differing geographical conditions like different amounts of mountains or lakes; it also encompasses the most complete set of physical barriers that may affect a large number of species.

Predictive models of landscape fragmentation

In the second part, this report investigates potential causes that contribute to an increased or decreased degree of landscape fragmentation and determines their relative importance. The density of the transportation network and the extent of landscape fragmentation are largely a function of interacting socioeconomic drivers such as population density and geophysical factors such as topography. Current levels of landscape fragmentation need to be interpreted within the context of these regional socioeconomic and geophysical conditions. Therefore, this report applies a set of statistical models to determine which of these factors drive the process of landscape fragmentation in Europe. We analysed the statistical relationships between landscape fragmentation and a range of predictive variables, applied these relationships to predict the likely fragmentation values for all regions in our study area, and compared actual values with predicted values.

In general, the most relevant variables affecting landscape fragmentation were population density, gross domestic product per capita, volume passenger density, and the quantity of goods loaded and unloaded per capita. The amount of variation in the level of fragmentation that was explained by the predictor variables was high, ranging from 46 % to 91 % in different parts of Europe. The statistical relationships indicated that different drivers of landscape fragmentation are important in different parts of Europe. Efforts for curtailing landscape fragmentation should take these differences into account.

Relevance for monitoring systems and policymaking

The results demonstrate that there is an urgent need for action. Large discrepancies between predicted and observed fragmentation values provide a basis for identifying areas for prioritising management action. Such data also provide a starting point for scenarios for the future development of landscape fragmentation in Europe. There is an increasing need and interest in including indicators of landscape fragmentation in monitoring systems of sustainable development, biodiversity, and landscape quality. We recommend that the results presented in this report be used for this purpose and be updated on a regular basis to detect trends in the development of landscape fragmentation. Therefore, this report discusses the use of fragmentation analysis presented in this report as a tool for performance review in transportation planning and regional planning and recommends a set of measures to control landscape fragmentation, such as more effective protection of remaining unfragmented areas and wildlife corridors, the setting of targets and limits and a European defragmentation strategy. This study provides for the first time an accurate measurement of landscape fragmentation for most of the European continent, which supports managers and policymakers in allocating resources towards the protection and restoration of biodiversity and landscape quality. The report also identifies future research needs.

1 What is landscape fragmentation?

1.1 Landscape fragmentation and its effects on the environment

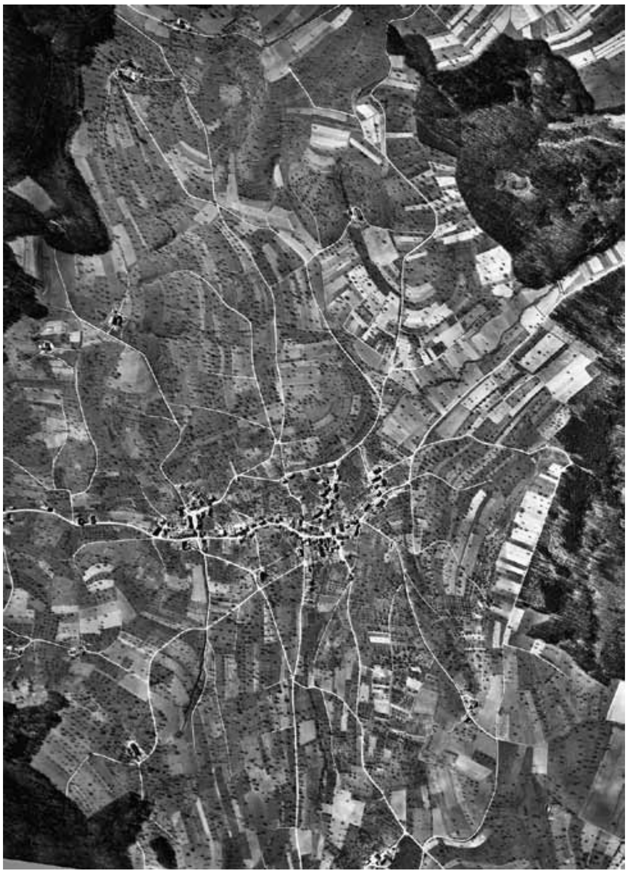
> 'Let's start by imagining a fine Persian carpet and a hunting knife. The carpet is 12 feet by 18, say. That gives us 216 square feet of continuous woven material. We set about cutting the carpet into 36 equal pieces, each one a rectangle, two feet by three. The severing fibres release small tweaky noises, like the muted yelps of outraged Persian weavers. When we're finished cutting, we measure the individual pieces, total them up — and find that, lo, there's still nearly 216 square feet of recognisably carpetlike stuff. But what does it amount to? Have we got 36 nice Persian throw rugs? No. All we're left with is three dozen ragged fragments, each one worthless and commencing to come apart.
>
> Now take the same logic outdoors and it begins to explain why the tiger, *Panthera tigris*, has disappeared from the island of Bali. It suggests why the jaguar, the puma, and 45 species of birds have been extirpated form a place called Barro Colorado Island — and why myriad other creatures are mysteriously absent from myriad other sites. An ecosystem is a tapestry of species and relationships. Chop away a section, isolate that section, and there arises the problem of unravelling.'
>
> From: David Quammen, *The Song of the Dodo*, 1996.

Over the last 50 years, the transport networks throughout the European continent have become increasingly dense and the urban areas have greatly expanded. Even though the resulting cumulative changes in the landscape have been dramatic, they have usually occurred in a gradual manner. As a consequence, these changes have not been easily perceived as dramatic by the general public. While single alterations are easily visible and assessed as 'not significant', their cumulative effects over longer periods of time are much more difficult to observe. Thus, single landscape alterations are easily marginalised and their cumulative impacts are underestimated. This has been called the 'pitfall of marginalisation'. Only after several decades can the full extent of the alterations and the resulting degradation of the landscape be evaluated (Figure 1.1).

Landscape fragmentation is the result of transforming large habitat patches into smaller, more isolated fragments of habitat. This process is most evident in urbanised or otherwise intensively used regions, where fragmentation is the product of the linkage of built-up areas via linear infrastructure, such as roads and railroads (e.g. Saunders et al., 1991; Forman 1995). Despite many improvements in legislation to better protect biodiversity, reduce pollution, and improve water quality, urban sprawl is still increasing and the construction of new transport infrastructure is continuing at a rapid pace. As a consequence, fragmentation of landscapes is rising and the remaining ecological network provides less and less connectivity.

Fragmentation has significant effects on various ecosystem services (Table 1.1). Up to a given density, there is a positive relationship between road density and the exploitation of specific services, since accessibility is a prerequisite for the supply of services. However, there is a trade-off between accessibility and service supply as the road network becomes too dense. This report mainly focuses on the species perspective (i.e. **Regulation and Maintenance services** according to the CICES classification; Haines-Young and Potschin 2010). Concerning Regulation and Maintenance services, a number of services might be seriously affected by increasing fragmentation, such as species movement, water-related services and erosion prevention. However, there are many other services that are at stake when it comes to fragmentation. Concerning **Provisional services**, we mention the consequences of fragmentation on food and timber production, e.g. reduced profit due to small land parcels, or reduced quality of agricultural products along roads. Another group of services that might be considerably influenced is the group of **Cultural services**. Although there is a positive relationship between accessibility and the potential use of landscapes for

Figure 1.1 Example of landscape change from Switzerland: aerial photographs of Arisdorf (canton of Basel-Country) from 1953 (left) and 1994 (right)



Note: The increase in fragmentation was caused by the motorway and growth of the built-up areas, and was intensified by reallocation of agricultural land and the removal of diverse landscape features such as fruit trees and hedgerows. In contrast, the forest areas have been strictly protected since 1902.

Source: Tanner 1999, © Federal Office of Topography swisstopo, reproduced by permission of swisstopo BA110233.

recreational purposes, negative impacts of roads on recreational use have been frequently reported. Large-scale assessment of ecosystem services is possible with look-up tables relating services to land use and other landscape properties (as done by Kienast et al., 2009). In a future study, a similar analysis could be performed with the fragmentation layers presented in this report.

The recent reports entitled 'Road construction market in central Europe 2010: Development forecasts and planned investments' (PMR publications, 2010) and 'Deployment on the trans-European transport network (TEN-T)' (European Commission, 2010a) presented calculations according to which the road construction market in central and eastern Europe will increase at the average nominal rate of 5 % in the coming years, with its value exceeding EUR 15 billion annually in 2012 and 2013. For example, Poland will exert the strongest influence on the road construction market by representing 40 % of the market's value due to sizeable investments in motorways unprecedented in Poland's history. Poland is currently preparing road infrastructure for the Euro 2012 football championships. In addition, 1 700 km of new motorways are expected to be constructed until 2013 in the five newly incorporated EU member countries: Bulgaria, the Czech Republic, Hungary, Romania and Slovakia. These trends in landscape change threaten many wildlife populations by reduced connectivity among the remaining habitat patches (e.g. Marzluff et al., 2001; Forman et al., 2003). Habitat patches are broken apart, reduced in size and increasingly isolated. In addition to the direct loss of habitat along linear infrastructure (area taken up by the infrastructure), an even higher amount of core habitat is lost due to edge effects (Figure 1.2). Smaller habitat patches easily lose keystone species, which contributes to the loss of biodiversity in many industrialised countries.

Table 1.1 Effects of landscape fragmentation on the environment and various ecosystem services

Theme	Consequences of linear infrastructure facilities
Land cover	• Land occupation for road surface and shoulders • Soil compaction, sealing of soil surface • Alterations to geomorphology (e.g. cuts, embankments, dams, stabilisation of slopes) • Removal of vegetation, alteration of vegetation
Local climate	• Modification of temperature conditions (e.g. heating up of roads, increased variability in temperature) • Accumulation of cold air at embankments of roads (cold-air build-ups) • Modification of humidity conditions (e.g. lower moisture content in the air due to higher solar radiation, stagnant moisture on road shoulders due to soil compaction) • Modification of light conditions • Modification of wind conditions (e.g. due to aisles in forests) • Climatic thresholds
Emissions	• Vehicle exhaust, pollutants, fertilising substances leading to eutrophication • Dust, particles (abrasion from tyres and brake linings) • Oil, fuel, etc. (e.g. in case of traffic accidents) • Road salt • Noise • Visual stimuli, lighting
Water	• Drainage, faster removal of water • Modification of surface water courses • Lifting or lowering of groundwater table • Water pollution
Flora and fauna	• Death of animals caused by road mortality (partially due to attraction of animals by roads or railways: 'trap effect') • Higher levels of disturbance and stress, loss of refuges • Reduction or loss of habitat; sometimes creation of new habitat • Modifications of food availability and diet composition (e.g. reduced food availability for bats due to cold air build-ups along road embankments at night) • Barrier effect, filter effect to animal movement (reduced connectivity) • Disruption of seasonal migration pathways, impediment of dispersal, restriction of recolonisation • Subdivision and isolation of habitats and resources, breaking up of populations • Disruption of metapopulation dynamics, genetic isolation, inbreeding effects and increased genetic drift, interruption of the processes of evolutionary development • Reduction of habitat below required minimal areas, loss of species, reduction of biodiversity • Increased intrusion and distribution of invasive species, pathways facilitating infection with diseases • Reduced effectiveness of natural predators of pests in agriculture and forestry (i.e. biological control of pest more difficult)
Landscape scenery	• Visual stimuli, noise • Increasing penetration of the landscape by roads, posts and wires • Visual breaks, contrasts between nature and technology; occasionally vivification of landscapes (e.g. by avenues with trees) • Change of landscape character and identity
Land use	• Consequences of increased accessibility for humans due to roads, increase in traffic volumes, increased pressure for urban development and mobility • Farm consolidation (mostly in relation with construction of new transport infrastructure) • Reduced quality of agricultural products harvested along roads • Reduced quality of recreational areas due to shrinkage, dissection, and noise

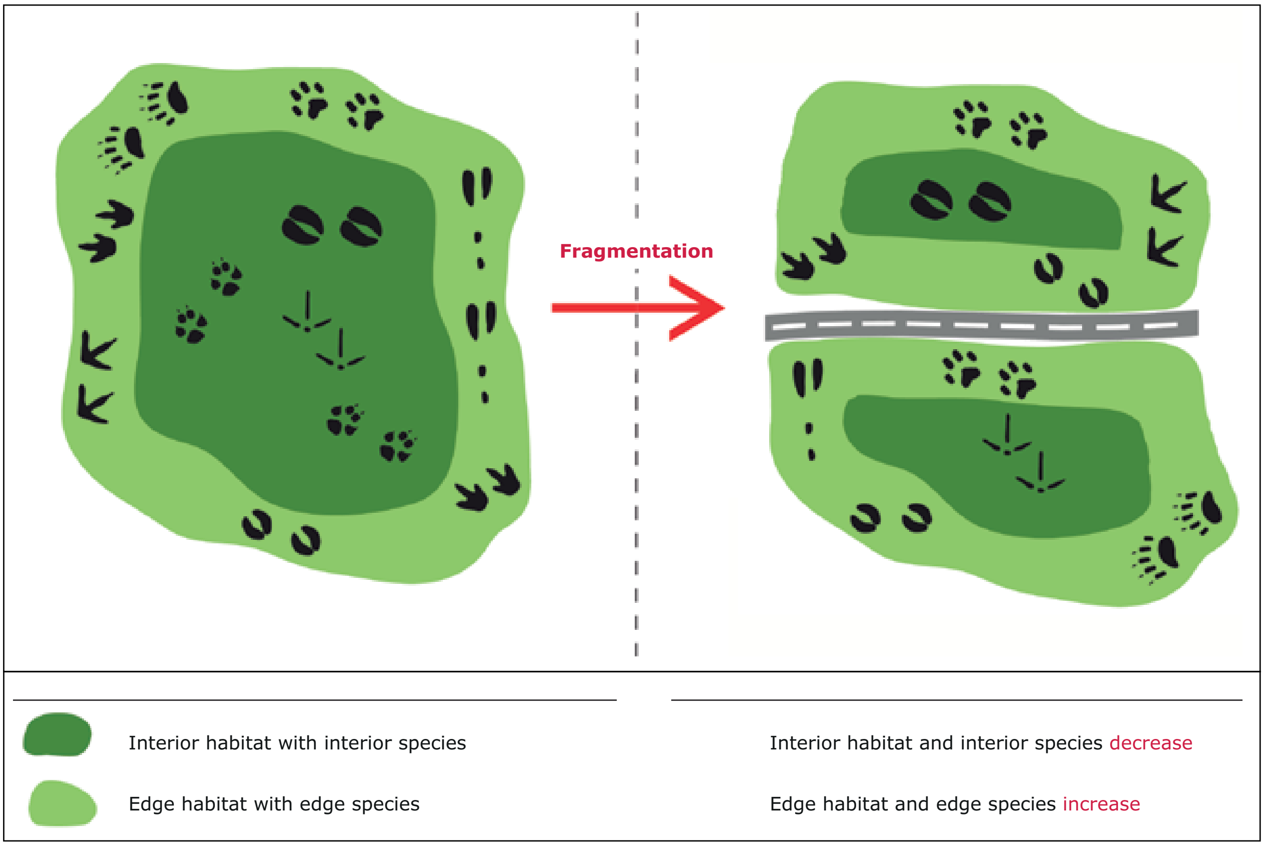
Note: Examples of the consequences of linear infrastructure facilities such as roads, railways and power lines (not including the effects of construction sites such as excavation and deposition of soils, vibrations, acoustic and visual disturbances). The effects are grouped into seven themes.

Source: Jaeger, 2003, based on various sources.

There is a growing body of evidence of negative ecological impacts of roads (Forman et al., 2003). Fahrig and Rytwinski (2009) reviewed 79 studies that provide data on population-level effects (abundance and density) and found that, overwhelmingly, roads and traffic have a negative effect on animal abundance, with negative effects outnumbering positive effects by a factor of five. The four main effects of roads and traffic that affect animal populations detrimentally are that they: decrease habitat amount and quality; enhance mortality due to collisions with vehicles; prevent access to resources on the other side of the road; and subdivide animal populations into smaller and more vulnerable fractions (Figure 1.3).

Many species need access to different types of habitat to be able to complete their life cycle. Roads also enhance human access to wildlife habitats and facilitate the spread of invasive species, and the subdivision and isolation of subpopulations interrupts metapopulation dynamics (Hanski 1999; Forman et al., 2003) and reduces genetic variability (Forman and Alexander, 1998; IUCN, 2001). Landscape fragmentation increases the risk of populations of becoming extinct (Figure 1.4), as isolated populations are more vulnerable to natural stress factors such as natural disturbances (e.g. weather conditions, fires, diseases), i.e. lower resilience. Landscape fragmentation is a major cause of the rapid decline of many wildlife populations. As landscape fragmentation contributes to the destruction of established ecological connections between adjoining areas of the landscape (Haber, 1993; Jaeger et al., 2005a), it also affects entire communities and ecosystems. The possibility for two animals of the same species to find each other in the landscape is a prerequisite for the persistence

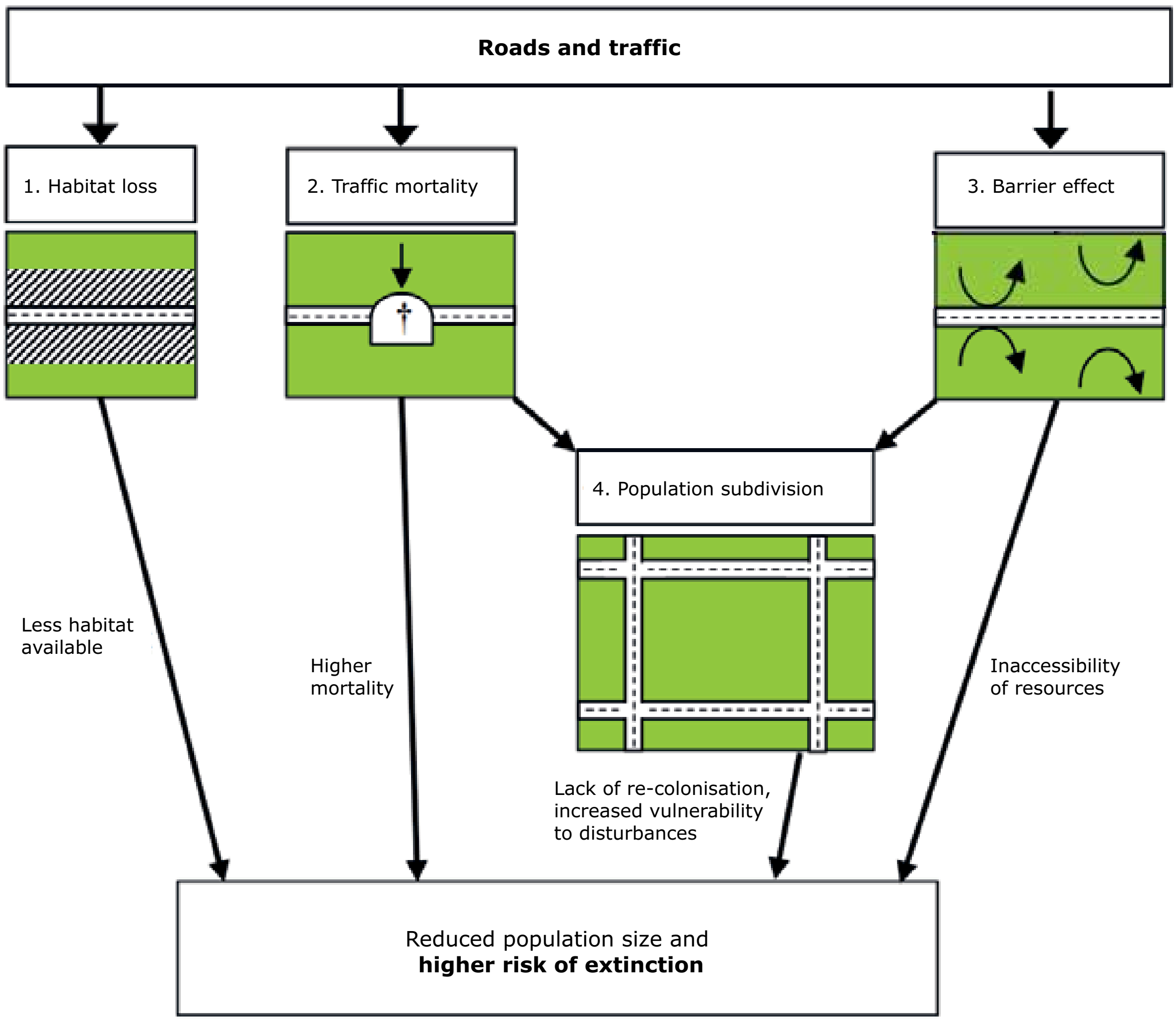
Figure 1.2 Illustration of the loss of core habitat (or interior habitat) caused by road construction cutting through a patch of habitat



Note: Core habitat is strongly reduced while edge habitat increases. Interior species, i.e. species requiring core habitat (shown in dark green) cannot survive in edge habitat (shown in light shading). Edge effects extend several hundred metres from the road. As a consequence, the loss of core habitat is much larger than the surface covered by linear infrastructure. The animal footprints illustrate the presence of different species in core habitat and edge habitat.

Source: Die Geographen schwick+spichtig (prepared for this report).

Figure 1.3 The four main effects of transportation infrastructure on wildlife populations



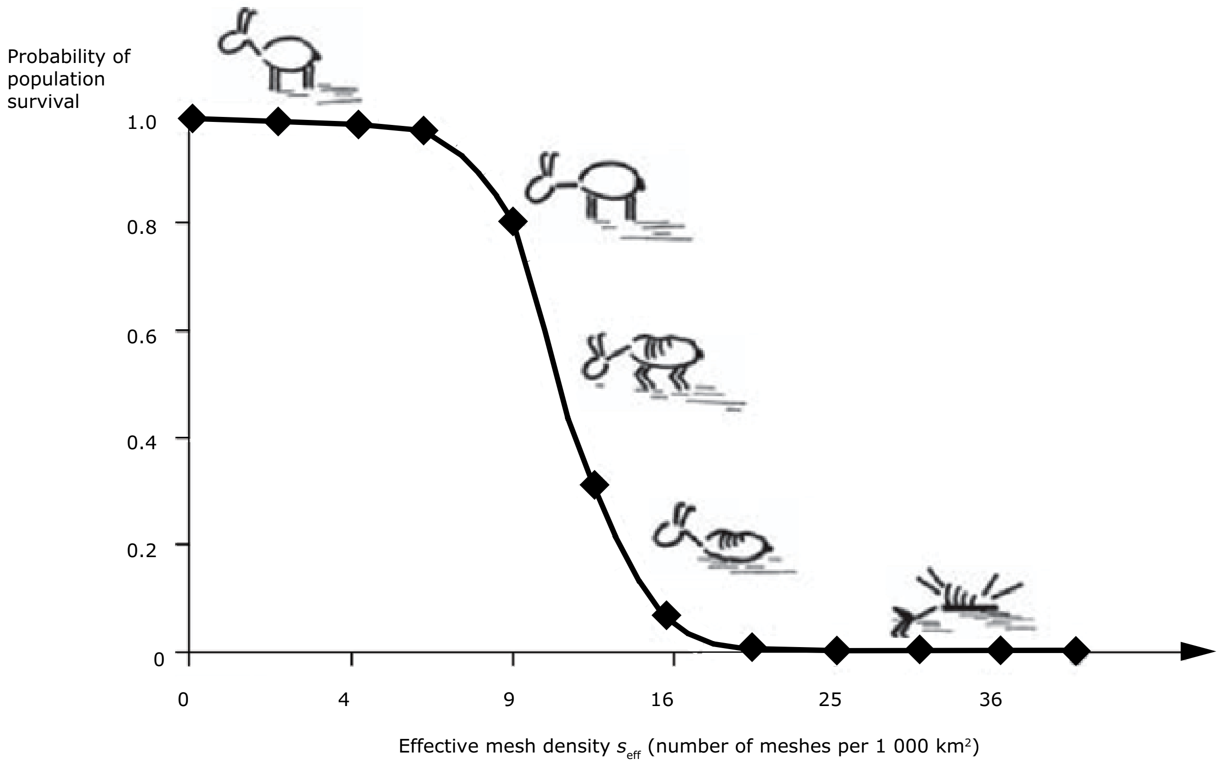
Note: Both traffic mortality and barrier effect contribute to population subdivision and isolation.

Source: From Jaeger et al., 2005b. Reproduced by permission of Elsevier.

of animal populations (e.g. because of the need for genetic exchange between populations and for the recolonisation of empty habitats). Table 1.1 includes only effects that are known. There may be various additional effects about which our knowledge is still very limited, such as cumulative effects (combination with other human impacts), response times of wildlife populations and effects on ecological communities (e.g. cascading effects). Therefore, the precautionary principle should be employed.

A prime example of the detrimental effects of landscape fragmentation by roads is the continuous decline of the brown hare (*Lepus europaeus*) populations in Switzerland as a consequence of landscape fragmentation by major roads in combination with intensive agricultural practices and loss of habitat (Figure 1.5). These landscape alterations have made the populations much more vulnerable to unfavourable weather conditions. The hare has been listed as endangered and its extinction seems impossible to prevent, as the 'point of no return' has probably been crossed several years ago. In the Czech Republic and in Austria, for instance, brown hare is one of the species most often killed by traffic (Glitzner et al., 1999; Hell et al., 2004). It is also listed in large parts of Germany where the populations are in decline, even though it once was one of the most abundant wildlife species in these landscapes. The construction of wildlife passages will not be sufficient to rescue this population because the amount of habitat and its quality are already too low due to the combined presence of

Figure 1.4 Illustration of thresholds in the effect of landscape fragmentation on the viability of wildlife populations



Note: The specific values of the thresholds depend on the particular species, traffic volumes on the roads, and the amount and quality of habitat present in the landscape (results of a computer simulation model). Once the threshold has been passed and the so-called 'point of no return' has been crossed, it will be impossible to rescue a declining population even with strong measures.

Source: Jaeger and Holderegger, 2005. Reproduced by permission of *GAIA — Ecological perspectives for science and society*.

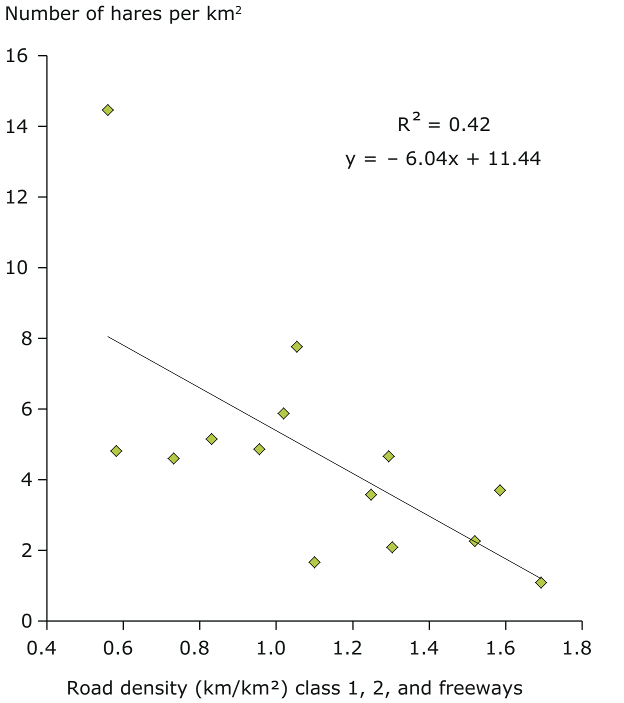
too many roads and intensive agriculture. Thus, connecting these remnants of habitat by including wildlife passages when new roads are constructed in this region is insufficient.

There is also evidence that red deer are no longer able to cross the plains in the Swiss lowlands between the Jura mountains and the Alps because of the accumulation of barriers. Therefore, the Swiss FOEN supported a project to establish a red deer population in the Jura mountains. Lynx are no longer able to cross the Reuss valley due to the high density of railway lines and highways, and the Swiss FOEN has initiated a project to establish a population in the Swiss Eastern Alpine regions. These examples illustrate the need to overcome the barrier effects of transportation infrastructure.

The story of the badger in the Netherlands is a more encouraging example. The observed decline of the badger populations in the 1970s was addressed by a national defragmentation programme established in 1984 (van der Grift, 2005). It included the construction of numerous culverts as so-called 'badger pipes', among other measures (Bekker and Canters 1997). The decline of badger populations was stopped, and the populations have even slightly increased since. However, wildlife passages can only be effective if there is still enough habitat left for the populations in the landscape (e.g. Fahrig, 2002). The effects of roads are the more detrimental to population viability, the lower the amount of habitat that is left in the landscape.

The extent of the negative impacts of habitat fragmentation on animal and plant populations is difficult to quantify since the full extent of the ecological effects of landscape alterations will only become evident decades afterwards (Figure 1.6). Even if all further landscape and habitat fragmentation were stopped, some wildlife populations would still disappear over the coming decades due to their long response times to the alterations that have already occurred. This effect has been called the 'extinction debt' of altered landscapes (Tilman et al., 1994). Therefore, indicators are needed that measure various pressures or threats to biodiversity. For

Figure 1.5 Effect of road network density on the abundance of brown hare in Canton Aargau, Switzerland



Note: Hare abundance was measured using spotlight taxations. Road classes included motorways and federal, main and side roads. Base units for regression analysis were raster grid cells (4 x 4 km^2) with 20–30 % forest edge area.

Source: From Roedenbeck and Voser, 2008. Reproduced by permission of Springer, Heidelberg, Germany.

example, the threat to biodiversity due to landscape fragmentation can be quantified by the 'mesh size' of the network created by the fragmenting elements present in the landscape (see Chapter 2).

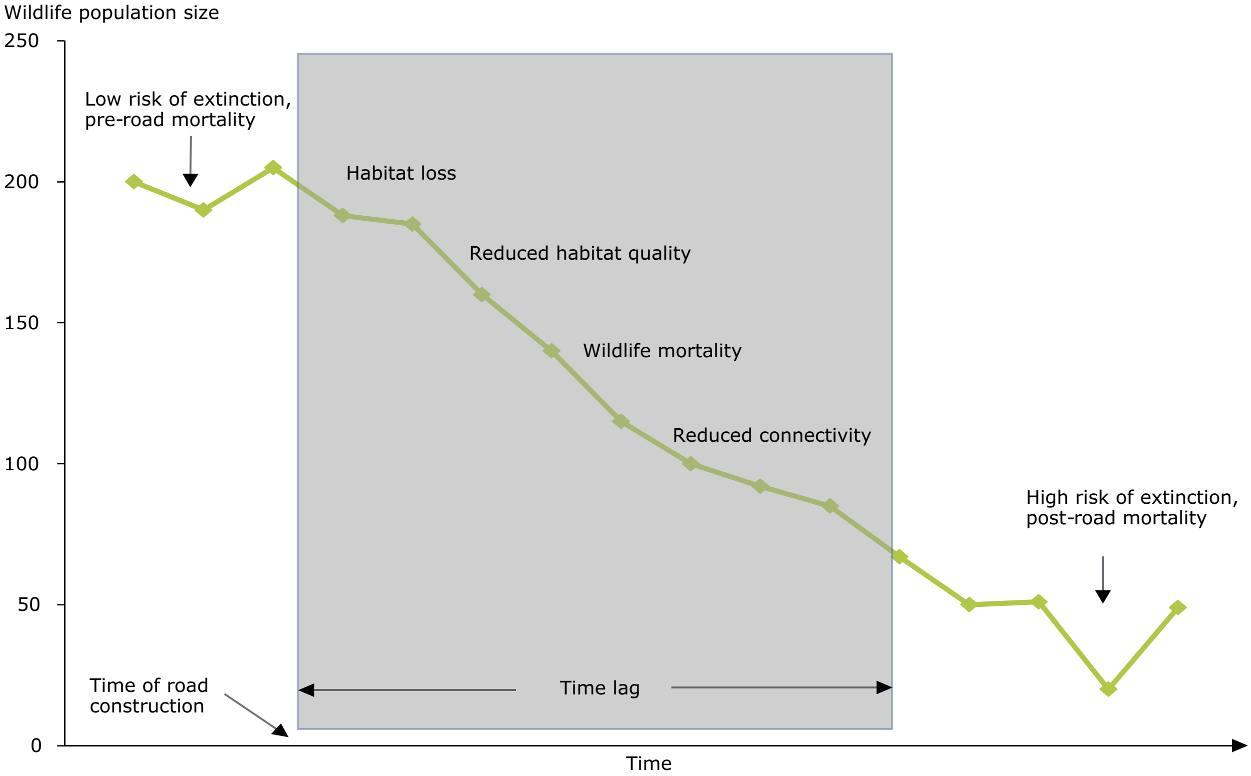
In addition, landscape fragmentation changes the landscape's appearance: areas of urban development, roads with high traffic volumes and railway lines are among the most striking features characterising the transformation of natural landscapes into cultural landscapes permeated by technology. As such landscapes usually cannot be experienced as connected any more, their fragmentation leads to a different perception of the landscape by humans (Di Giulio et al., 2009). The wider spread of noise and air pollution associated with the pervasiveness of roads also has negative effects on the recreational quality of landscapes that are important for humans as well.

The purpose of this report is to quantify landscape fragmentation for all countries in Europe for which the necessary data are available (28 countries). The report applies the method of fragmentation analysis that had previously been used in Switzerland under the commission of the Swiss Federal Office for the Environment (FOEN), after some adjustments were made according to the availability of data. The report is the outcome of collaboration between the Swiss FOEN and the EEA. The seven questions of investigation addressed by the report are listed in Section 1.3. The report considers fragmentation caused by transportation infrastructure and built-up area. It therefore provides a conservative assessment of the current levels of fragmentation, as other anthropogenic alterations of the landscapes in Europe also contribute to fragmentation (e.g. intensive agriculture, fences). Landscape fragmentation often goes hand in hand with a degradation of the quality of the remaining habitats due to the intensification of land use and the removal of diverse typical landscape features such as hedgerows and fruit trees. Therefore, the threat to biodiversity related to landscape fragmentation that is analysed in this report is only one of a series of threats that also need to be addressed.

1.2 Socioeconomic drivers of landscape fragmentation

Landscape fragmentation is the outcome of complex interactions between policy, geophysical characteristics of the landscape and socioeconomic drivers of development (Munroe et al., 2005). Even though there is a general agreement about the negative effects of landscape fragmentation, the interactions between geophysical, ecological and anthropogenic factors are still poorly understood. However, such information is essential for management and restoration efforts (Laurance, 1999; Geist and Lambin, 2001; Bayne and Hobson, 2002). Relevant studies in road ecology have had some influence on management decisions (Beckmann et al., 2010), but this process has been very slow, and landscape-scale effects of road networks have rarely been studied (Roedenbeck et al., 2007; van der Ree et al., 2011). As a consequence, the fast pace of road development by far exceeds our increase in understanding the effects on the environment and biodiversity, which makes appropriate adaptive management impossible. In addition, the uncertainties about ecological effects of roads are not taken seriously enough in the planning process, which contributes to the 'spiral of landscape fragmentation' (Jaeger, 2002). This results in a lack of accountability for the majority of uncertain effects and effects that become manifest years after the construction of new transportation infrastructure due

Figure 1.6 Four ecological impacts of roads on animal populations and the time lag for their cumulative effect



Note: After the time lag (often in the order of decades), population size is smaller, exhibits greater relative fluctuations over time and is more vulnerable.

Source: Modified after *Road Ecology* by Richard T.T. Forman et al. Copyright © 2003 Island Press. Reproduced by permission of Island Press, Washington, DC.

to the long response times of wildlife populations. Pressured by compelling economic and social arguments for road construction, the ecological effects associated with roads have been underestimated and considered of second importance by decision-makers (Caid et al., 2002). Therefore, studies are urgently needed that address the driving forces of landscape fragmentation. However, such studies that combine biological, geophysical and socioeconomic data on regional or national scales are rare (Tang et al., 2006; Turner et al., 2007).

A consistent finding of studies about land-cover change that include socioeconomic information is that the extent and pace of land-cover change is often inversely related to distance to urban centres (Turner, 1990; LaGro and DeGloria, 1992; Turner et al., 1996). These studies report a general tendency that landscape fragmentation is highest in the vicinity of urban centres and much lower in areas distant from cities. These findings are supported by theories in economic geography such as Clark's (1951) 'exponential decay model of population density', which predicts that economic activities decline with distance from a city centre. Such theories postulate that the demand for land for human use is proportional to population density and inversely proportional to the distance from the population centres. As demand for land declines, so should the extent of landscape fragmentation (Munroe et al., 2005).

Based on these considerations, we hypothesised that a region is likely to be more fragmented than other regions if it has higher population density, higher gross domestic product per capita, a lower unemployment rate and higher volumes of goods and passengers transported, with a population that is well educated and environmentally aware (as a response to advanced environmental degradation), with fewer natural barriers (e.g. few high mountains), and if the region is already naturally broken up into islands. The influence of hills (areas of low elevation with gentle slopes, but not lowland) would be expected to differ between various parts of Europe (i.e. to show a positive relationship in regions with little lowland area and a negative relationship in regions with larger amounts of lowlands).

1.3 Landscape fragmentation in Europe: research questions and main results

Most countries in Europe are now emphasising the need to preserve biodiversity and ensure connectivity between the remaining natural areas for the movement of animals, including migration and dispersal, for access to different types of habitats and other resources, for recolonisation of empty habitats and for genetic exchange between populations. The UN Convention on Biological Diversity considers fragmentation by infrastructure and other land use a major threat to the populations of many species. This is reflected in the pan-European biological and landscape diversity strategy (PEBLDS) (http://www.strategyguide.org), the European Community biodiversity strategy (European Commission 1998), and the Habitats Directive (92/43/EEC, 1992). The programme SEBI2010 ('Streamlining European 2010 biodiversity indicators') has initiated a collaboration between the EEA, PEBLDS (based on the Council of Europe and the UNEP Regional Office for Europe), European Centre for Nature Conservation (ECNC), UNEP-World Conservation Monitoring Centre (UNEP-WCMC), and the European Commission to monitor biodiversity in Europe. However, in many regards, the discrepancy between the political objectives and the real development has grown. For

Box 1.1 Explanation of the most important technical terms used in this report

FG FG-A1 FG-A2 FG-B2	A **fragmentation geometry** (FG) is a set of various types of barriers that are considered relevant in a landscape. These barriers are combined in a digital dataset to determine the degree of fragmentation of the landscape by calculating the effective mesh density. Different objectives of an investigation may require different fragmentation geometries. This report applies three fragmentation geometries: FG-A1 = Major anthropogenic fragmentation; FG-A2 = Major and medium anthropogenic fragmentation; FG-B2 = Fragmentation of non-mountainous land areas. For further information see Section 2.3.
m_{eff}	The **effective mesh size** (m_{eff}) serves to measure landscape connectivity, i.e. the degree to which movement between different parts of the landscape is possible. It expresses the probability that any two points chosen randomly in a region are connected; that is, not separated by barriers such as transport routes or built-up areas. The more barriers fragmenting the landscape, the lower the probability that the two points are connected, and the lower the effective mesh size. m_{eff} is measured in km².
s_{eff}	The **effective mesh density** (s_{eff}) is a measure of landscape fragmentation, i.e. the degree to which movement between different parts of the landscape is interrupted by barriers. It gives the effective number of meshes per 1 000 km², in other words, the density of the meshes. This is easy to calculate from the effective mesh size: It is simply a question of how many times the effective mesh size fits into an area of 1 000 km². The more barriers fragmenting the landscape, the higher the effective mesh density. For further information see Sections 2.1 and 2.2.
NUTS-X	The **Nomenclature of Statistical Territorial Units** (NUTS) is a hierarchical system for dividing up the territory of the EU for the purpose of the collection of regional statistics, socioeconomic analyses of the regions and framing of policies. NUTS-X denotes a combination of NUTS-2 (basic regions for the application of regional policies) and NUTS-3 (small regions for specific diagnoses).
LEAC grid	This grid is the European reference grid used for activities in the frame of **Land and Ecosystem Accounting** (LEAC) and other tasks. It has a resolution of 1 km².
CLC	**Corine land cover** (CLC) is a digital map of land cover types in Europe that is consistent across the continent, based on satellite images. This map is useful for environmental analysis and assessment and for policymaking. CLC 2006 is the third dataset in a series, the previous datasets corresponding to 1990 and 2000.
TeleAtlas	TeleAtlas is a provider of digital maps for navigation services, covering 200 countries around the world. The data of roads and railways used in this report were taken from the **TeleAtlas** 2009 dataset.

Note: A complete list of acronyms is given on page 68.

example, the federal government of Germany called for a 'trend reversal in landscape fragmentation and widely dispersed urban sprawl' more than 25 years ago (Bundesminister des Innern 1985), but the trends have largely continued unabated since.

The EU COST Action 341 studied the problems caused by habitat fragmentation due to transportation infrastructure (COST Action 341, 2000). It has produced a 'European handbook on habitat fragmentation due to transportation infrastructure' (Iuell et al., 2003) and various national reports (available at http://www.iene.info). Accordingly, many countries now have guidelines for road and rail construction that involve at least some mitigation measures, such as the construction of wildlife passages. The next important task is to integrate habitat fragmentation into transportation planning and monitoring studies and to develop agreements about environmental standards such as limits and targets aiming at curtailing landscape fragmentation. For example, Switzerland has already included time series of landscape fragmentation in monitoring systems at the federal level, using the same method as is used in this report for the European level. The EEA has formerly used 'average size of non-fragmented land parcels' as a measure of landscape fragmentation for environmental monitoring (e.g. EEA, 2002). However, this method is insufficient for several reasons: for example, it gives small parcels the same weight as large parcels. As a consequence, the measure cannot distinguish between the fragmentation of small parcels and large parcels. Therefore, the EEA has successfully tested the new and more reliable method called 'effective mesh size' (Jaeger, 2000; Moser et al., 2007) for their purposes and found that this method successfully overcomes the weaknesses of the previous method. The new method is applied in this report. The present study is the logical next step in these efforts to bridge the gap between regional studies and the continental scale where driving forces of landscape fragmentation operate (e.g. socioeconomic drivers).

This study quantifies the degree of landscape fragmentation caused by transportation infrastructure and built-up areas in 28 countries in Europe (for which data were available) for the first time. We refer to this group of countries as the '28 countries investigated'. When we write about the level of fragmentation in Europe, we also refer to this group of 28 countries investigated, even though Europe includes many more countries. This study also determines where fragmentation is highest and lowest, and identifies socioeconomic factors that are most likely to explain the observed patterns of landscape fragmentation. The report provides a baseline to measure landscape fragmentation and to track changes in landscape fragmentation in the future. The effectiveness of policies of landscape protection can then be evaluated through comparison with these time series of landscape fragmentation. Accordingly, the most important research questions of this study were:

1. What is the current degree of landscape fragmentation in Europe at different spatial scales (countries, NUTS-X regions, 1-km^2 LEAC grid)?

2. What are the differences between the countries and between the various NUTS-X regions?

3. What are the relationships between the degree of landscape fragmentation and socioeconomic and geophysical factors?

4. What is the relative importance of these factors, i.e. which factors determine the degree of landscape fragmentation in Europe?

5. Which statistical models are the most suitable to predict the degree of landscape fragmentation in Europe?

6. Which regions in Europe exhibit higher or lower degrees of landscape fragmentation than the level predicted by the predictive model? What are potential causes of why some regions are more or less fragmented than expected?

7. What are the implications of these results and how can they be applied to traffic planning and regional planning in Europe?

The number of fragmenting elements considered in our analysis was limited, even though different wildlife species perceive various types of roads differently. These differences could be considered by applying more specific fragmentation geometries (particular combinations of fragmenting elements in the landscape) for each species. This would make the results more appropriate for consideration of the effects of landscape fragmentation on biodiversity. However, consideration of many species with different fragmentation geometries would produce many more indicators than appropriate for most monitoring systems, and the very concept of an indicator is to not cover everything, but to choose particularly relevant examples that are indicative of other processes as well. This study was also limited by the availability of consistent datasets across Europe. Fragmentation of watercourses by dams is another relevant issue for aquatic biodiversity, but was not included in this analysis because this report focuses on the fragmentation of land areas.

This report provides a first assessment of landscape fragmentation at the European level, and provides a basis for future systematic assessments of changes over time. The results are presented for more than 500 NUTS-X regions in 28 countries in Europe. We believe that the results provided by this study will contribute to improving the context for ecological conservation and more sustainable transportation planning throughout the European continent.

The effective mesh density values across the 28 investigated countries cover a large range, from low values (less than 1 mesh per 1 000 km^2) in large parts of Scandinavia to very high fragmentation values in western and central Europe. Low levels of fragmentation are usually associated with mountain ranges or remoteness. Many highly fragmented regions in Belgium, the Netherlands, Denmark, Germany, France, Poland and the Czech Republic have effective mesh density values above 20 meshes per 1 000 km^2. Such high fragmentation values are mostly found in the vicinity of large urban areas and along major transportation corridors. The highest values of the effective mesh density of more than 1 000 meshes per 1 000 km^2 were found in some heavily urbanised regions (e.g. Brussels, Paris, London). The values differ between the three fragmentation geometries (for their explanation, see Box 1.1). The effective mesh density is much higher in FG-A2 than in FG-A1 because FG-A2 includes more barriers. In turn, FG-B2 has higher values than FG-A2 as lakes and mountains were considered as barriers and excluded from the reporting units in FG-B2, but the differences between FG-B2 and FG-A2 are much smaller than between FG-A2 and FG-A1. Fragmentation geometry B2 'Fragmentation of non-mountainous land areas', which includes highways up to class 4, railways, and urban areas, is the most important fragmentation geometry, as it is suitable for comparing regions with differing geographical conditions like different amounts of mountains or lakes; it also encompasses the most complete set of physical barriers that affect a large number of species. Future studies about additional points in time will allow for temporal comparisons to assess the rate of increase of landscape fragmentation.

In general, the most relevant variables affecting landscape fragmentation were population density, gross domestic product per capita, volume passenger density and the quantity of goods loaded and unloaded per capita. The amount of variation in the level of fragmentation that was explained by the predictor variables was high and ranged from 46 % to 91 %. The results indicated that different parts of Europe have different drivers of landscape fragmentation. Efforts for curtailing landscape fragmentation should take these differences into account.

There is an increasing need and interest in including indicators of landscape fragmentation in monitoring systems of sustainable development, biodiversity and landscape quality. The results presented in this report should be used for this purpose and should be updated on a regular basis to detect trends in the development of landscape fragmentation. The results demonstrate that there is an urgent need for action. Therefore, this report discusses the use of fragmentation analysis as a tool in transportation planning and regional planning and for performance review, and recommends a set of measures to control landscape fragmentation, such as more effective protection of the remaining unfragmented areas and the setting of targets and limits. The report also identifies future research needs.

2 How to measure landscape fragmentation?

2.1 Methods for measuring landscape fragmentation

Many landscape metrics have been used for quantifying landscape fragmentation (Gustafson, 1998; Leitão et al., 2006). All these metrics have particular strengths and weaknesses. It is important to use a reliable measure when producing time series of landscape fragmentation for monitoring the state of the landscape and changes over time. Therefore, the behaviour of newly proposed metrics needs to be carefully studied and compared with existing metrics before they are applied (Li and Wu, 2004).

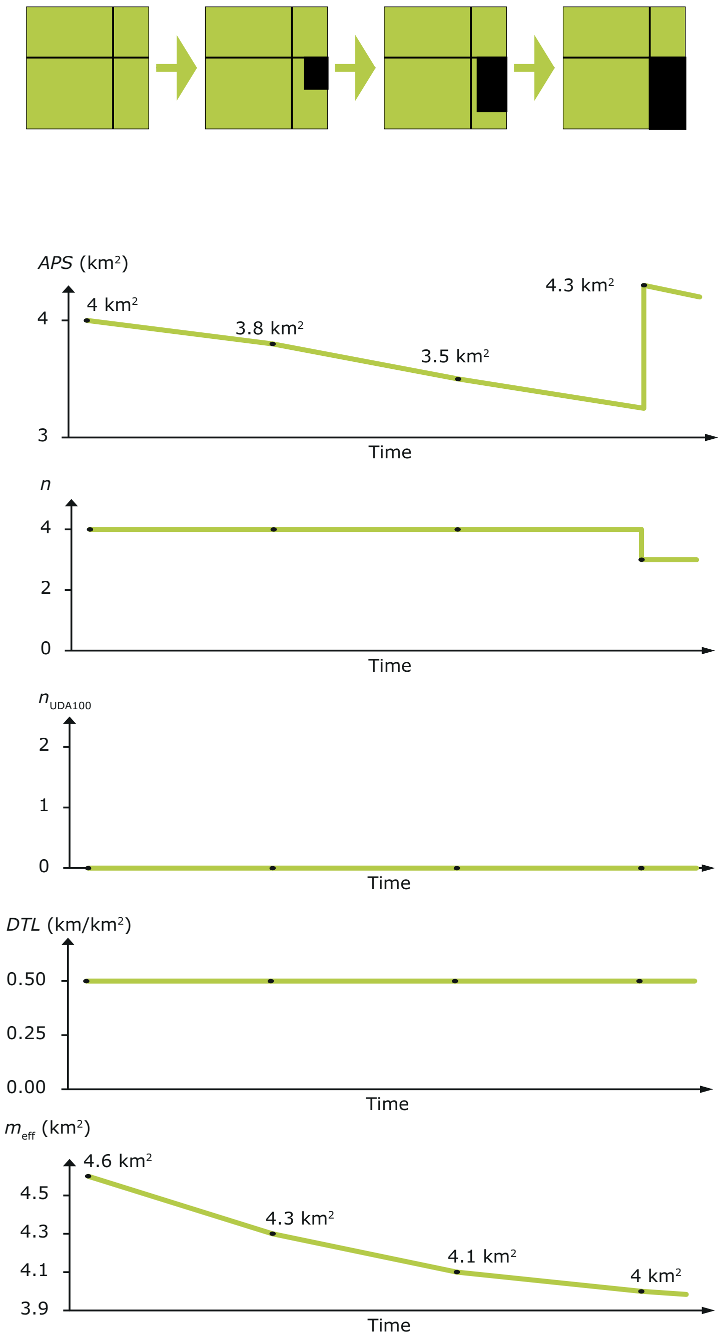
For example, the average size of remaining non-fragmented land parcels (or for short: average patch size, *APS*), density of transportation lines (*DTL*; in relation to total area of the landscape), and the number of the remaining large undissected low-traffic areas larger than 100 km^2 (n_{UDA100}) have been suggested as measures of fragmentation. A measure of fragmentation that has been introduced more recently, is the method of the effective mesh size and effective mesh density (Jaeger, 2000, see below). This method is used in this report because it has several advantages over most other landscape metrics.

- It takes account of all patches remaining in the 'network' of transportation infrastructure and urban zones.
- It is suitable for comparing the fragmentation of regions with differing total areas and with differing proportions occupied by housing, industry, and transportation structures.
- Its reliability has been confirmed on the basis of nine suitability criteria through a systematic comparison with other quantitative measures (Jaeger, 2000, 2002; Girvetz et al., 2007). The suitability of other metrics was limited as they only partially met the criteria.
- It can be extended to include the permeability of transportation infrastructure for animals or humans moving in the landscape (i.e. filter effect; Jaeger, 2002, 2007).

One reason why the average patch size is not a suitable metric of the degree of fragmentation is that it does not react consistently to different fragmentation phases, e.g. it **decreases** when habitat patches are dissected, when habitat size decreases, or when large patches are lost, but it **increases** when small patches are lost (see Jaeger, 2000, 2002 for a more detailed discussion). We illustrate the comparison of these four metrics with m_{eff} based on their behaviour in the phases of shrinkage and attrition of patches, which contribute to landscape fragmentation (Forman, 1995). The example in Figure 2.1 illustrates that the average patch size, the number of remaining patches, the number of large undissected low-traffic areas > 100 km^2, and the density of transportation lines do not behave in a suitable fashion in the phases of shrinkage and attrition. Therefore, the suitability of these four measures for the purpose of quantifying the degree of landscape fragmentation is limited.

Another example is the comparison of two landscapes where the road network is either bundled or distributed evenly across the landscape (Figure 2.2). Road density and average patch size are insensitive to this difference, but effective mesh size indicates the difference properly. This example illustrates that effective mesh size expresses differences in the spatial arrangement of transportation routes.

Figure 2.1 Illustration of the behaviour of five landscape metrics in the phases of shrinkage and attrition of the remaining parcels of open landscape due to the growth of an urban area



Calculations:

APS = (sum of four patches/4), followed by a jump to *APS* (sum of three patches/3).

Number of patches: $n = 4$, than changes abruptly to $n = 3$.

No patches are larger than 100 km², thus n_{UDA100} does not capture the changes in the landscape.

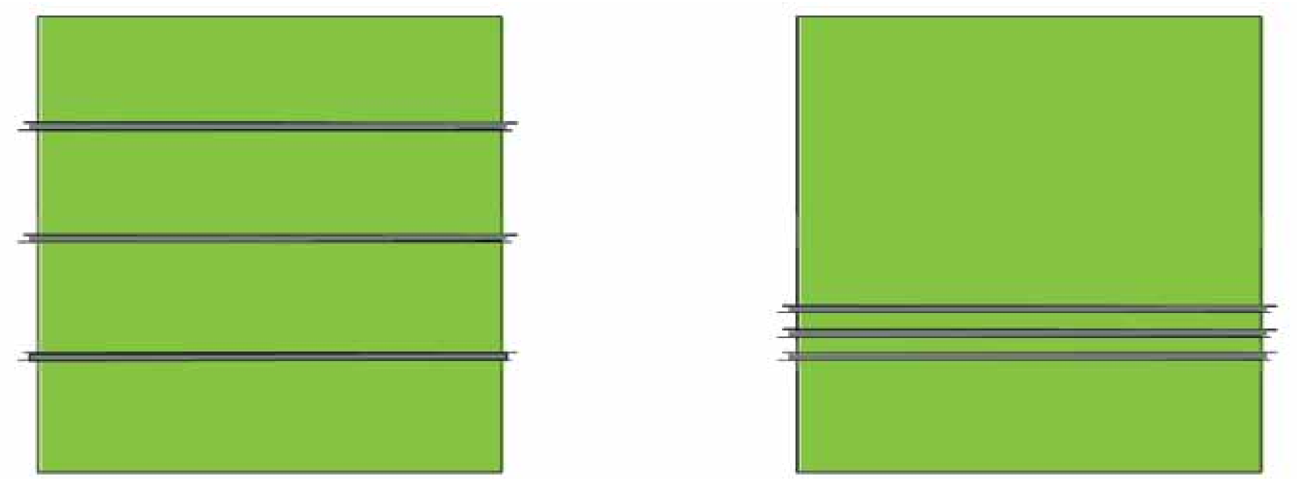
The lenght of the roads stays constant at 2 x 4 km/16 km² = 8 km/km².

The value of m_{eff} is calculated as shown in Box 2.2.

Note: First row: change of the landscape over time (black lines = highways, black area = residential or commercial area; size of the landscape: 4 km × 4 km = 16 km²). Only the effective mesh size behaves in a suitable way (bottom diagram). *APS* and *n* both exhibit a jump in their values (even though the process in the landscape is continuous); *DTL* and n_{UDA100} do not respond to the increase in fragmentation. (m_{eff} = effective mesh size, n = number of patches, *APS* = average patch size, n_{UDA100} = number of large undissected low-traffic areas > 100 km², *DTL* = density of transportation lines).

Source: J. Jaeger (prepared for this report).

Figure 2.2 Illustration of two landscapes where the roads are distributed evenly (left) or bundled together (right)



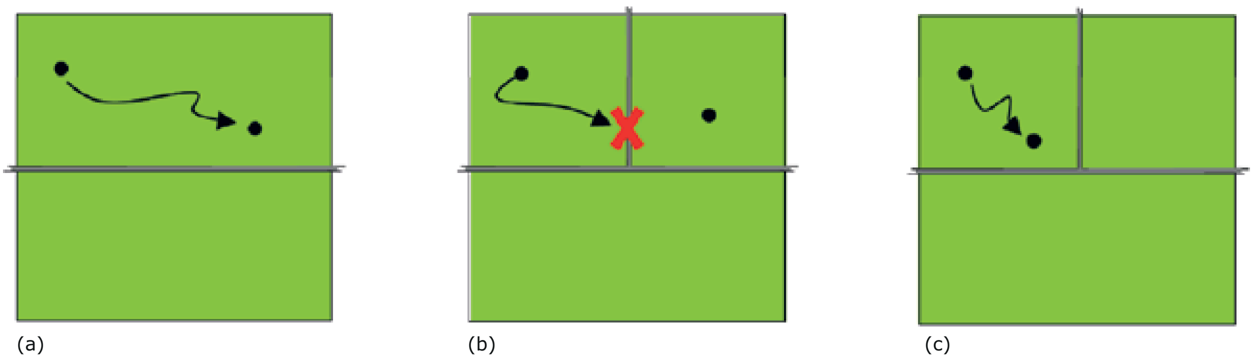
Note: The landscape on the left is more fragmented, and the landscape on the right contains more undisturbed core habitat. However, the density of transportation lines (*DTL*) is the same in both landscapes (0.5 km/km^2, when the landscape is of size 64 km^2). The number of remaining patches (*n*) and the average patch size (*APS*) do not indicate the structural differences between the two landscapes, either, as they are the same in both landscapes (n = 4; *APS* = 16 km^2). The effective mesh size (m_{eff}), however, correctly indicates the difference between the landscape on the left (m_{eff} = 16 km^2) and on the right (m_{eff} = 37.7 km^2).

Source: Jaeger et al., 2007.

2.2 Effective mesh size and effective mesh density

To measure the degree of landscape fragmentation, we applied the method of the effective mesh size (m_{eff}), which is based on the probability that two points chosen randomly in a region are connected, i.e. are located in the same patch (Jaeger, 2000). This can be interpreted as the probability that two animals, placed in different locations somewhere in a region, can find each other within the region without having to cross a barrier such as a road, urban area, or major river. Thus, it indicates the ability of animals to move freely in the landscape without encountering such barriers. If one of the points (or both) is located within a fragmenting landscape element, for example in an urban area, it is separated from all other points.

Figure 2.3 Illustration of the basic idea of the effective mesh size metric



Note: Two randomly chosen points in the landscape may be connected (a) or separated by a barrier, i.e. when a new road is added to the landscape (b). The more barriers in the landscape, the fewer points are connected with any given point (c), and the lower the effective mesh size. The effective mesh size is an expression of the probability of any two randomly chosen points in the landscape being connected. This corresponds to the definition of landscape connectivity as 'the degree to which the landscape facilitates or impedes movement among resource patches' (Taylor et al., 1993). Landscape fragmentation means a reduction in landscape connectivity.

Source: J. Jaeger (prepared for this report).

By multiplying this probability by the total area of the reporting unit, it is converted into the size of an area which is called the **effective mesh size**. The smaller the effective mesh size, the more fragmented the landscape.

The effective mesh size (m_{eff}) has several highly advantageous mathematical properties, e.g. m_{eff} is relatively unaffected by the inclusion or exclusion of small or very small patches (Jaeger, 2000, 2002). The maximum value of the effective mesh size is reached with a completely unfragmented area: m_{eff} then equals the size of the whole area. If an area is divided up into patches of equal size, then m_{eff} equals the size of these patches. However, m_{eff} is not usually equal to the average size of the patches. The minimum value of m_{eff} is 0 km^2; such is the case where a region is completely covered by transportation and urban structures (Box 2.1).

An important strength of this measure is the fact that it describes the spatial structure of a network of barriers in an ecologically meaningful way using only one value that is easy to understand (Figure 2.2). The goal of using landscape metrics to assess landscape fragmentation is to gain insight into landscape-level ecological processes associated with species movements, such as foraging, dispersal, genetic connectivity, and metapopulation dynamics, which depend on the ability to move through the

Figure 2.4 Barriers in the landscape (left) and the corresponding effective mesh size represented in the form of a regular grid (right)

Source: Bertiller et al., 2007.

Box 2.1 Definition of effective mesh size m_{eff} and effective mesh density s_{eff}

The definition of the **effective mesh size** m_{eff} is based on the probability that two points chosen randomly in an area are connected and are not separated by any barriers. This leads to the formula:

$$m_{eff} = \left(\left(\frac{A_1}{A_{total}} \right)^2 \left(\frac{A_2}{A_{total}} \right)^2 + \left(\frac{A_3}{A_{total}} \right)^2 + \ldots + \left(\frac{A_n}{A_{total}} \right)^2 \right) \cdot A_{total} = \frac{1}{A_{total}} \sum_{i=1}^{n} A_i^2$$

where n is the number of patches, A_1 to A_n represent the patch sizes from patch 1 to patch n, and A_{total} is the total area of the region investigated.

The first part of the formula gives the probability that two randomly chosen points are in the same patch. The second part (multiplication by the size of the region) converts this probability into a measure of area. This area is the 'mesh size' of a regular grid pattern showing an equal degree of fragmentation (Figure 2.4) and can be directly compared with other regions. The smaller the effective mesh size, the more fragmented the landscape.

The **effective mesh density** s_{eff} gives the effective number of meshes per km², in other words the density of the meshes. It is often more convenient to count the effective number of meshes per 1 000 km² rather than per 1 km² (the difference is visible in the unit following the number). This number is very easy to calculate from the effective mesh size: It is simply a question of how many times the effective mesh size fits into an area of 1 000 km².

For example, for m_{eff} = 25 km², the corresponding effective mesh density is s_{eff} = 1 mesh/(25 km²) = 0.04 meshes per km² = 40 meshes per 1 000 km².

This relationship is therefore expressed as:

$$s_{eff} = \frac{1\ 000\ km^2}{m_{eff}} \frac{1}{1\ 000\ km^2} = \frac{1}{m_{eff}}$$

The effective mesh density value rises when fragmentation increases (Figure 2.5). The two measures contain the same information about the landscape, but the effective mesh density is more suitable for detecting trends and changes in trends. A detailed description of both metrics can be found in Jaeger (2000, 2002).

landscape and between habitat patches. Landscape fragmentation can be understood as a reduction in landscape connectivity, which is defined as 'the degree to which the landscape facilitates or impedes movement among resource patches' (Taylor et al., 1993; Tischendorf and Fahrig, 2000). When landscapes become more and more fragmented then the movement of animals among their resource patches is increasingly impeded. Consequently, the degree of landscape fragmentation increases.

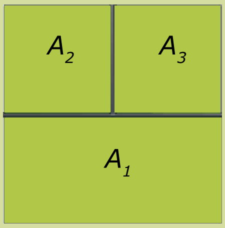
The effective mesh size is a direct quantitative expression of landscape connectivity; in fact, the effective mesh size corresponds directly with the suggestion by Taylor et al. (1993) that 'landscape connectivity can be measured for a given organism using the probability of movement between all points or resource patches in a landscape.'

As a consequence, this method has substantial advantages, e.g. it meets all scientific, functional, and pragmatic requirements of environmental indicators (see Jaeger et al., 2008, for a systematic assessment of effective mesh size based on 17 criteria for the selection of indicators for monitoring systems of sustainable development).

The effective mesh size has been widely implemented as an indicator for environmental monitoring by various countries, e.g. m_{eff} is now officially implemented in Switzerland (Bertiller et al., 2007; Jaeger et al., 2007, 2008), Germany (as one out of 24 core indicators in the National Sustainability Report and in the National Strategy on Biological Diversity; Schupp, 2005; Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2007), Baden-Württemberg

Box 2.2 A simple example of calculating m_{eff} and s_{eff}

Consider a landscape that is fragmented by highways into three patches:



Note: A_{total} = 2 km x 2 km = 4 km²

The probability that two randomly chosen points will be in patch 1 (and therefore connected) is:

$$\left(\frac{A_1}{A_{total}}\right)^2 = 0.5 \times 0.5 = 0.25$$

The corresponding probability is $0.25^2 = 0.0625$ for both patches 2 and 3. The probability that the two points will be in patch 1 or 2 or 3 is the sum of the three probabilities which results in 0.375.

Multiplying this probability by the total area of the region investigated finally gives the value of the effective mesh size:
$m_{eff} = 0.375 \times 4\ km^2 =$ **1.5 km²**

The effective mesh density s_{eff} is then:
s_{eff} = 666.7 meshes per 1 000 km²

The relationship between mesh density and mesh size is such that a percentile increase in mesh density is different from a percentile decrease in mesh size (Figure 2.5). For example, an increase in effective mesh density of 100 % (e.g. from 20 to 40 meshes per 1 000 km²) corresponds to a decrease in effective mesh size of 50 % (e.g. from 50 to 25 km²).

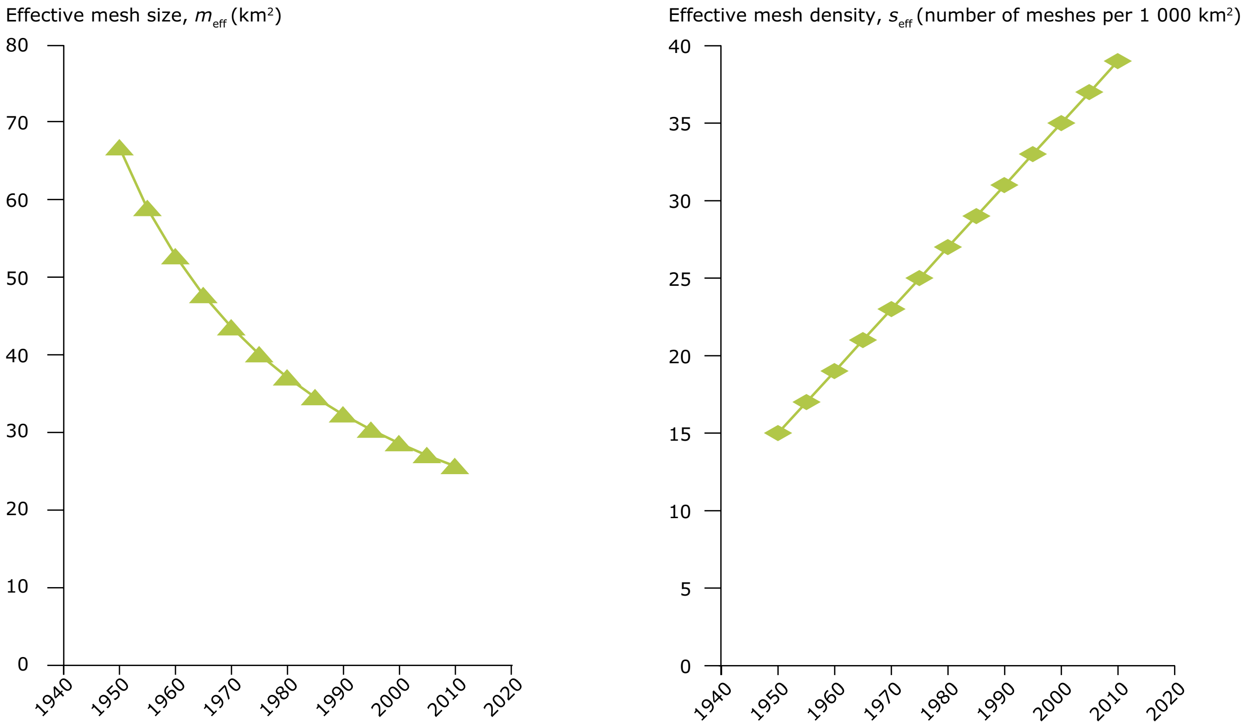
(State Institute for Environment, Measurements and Nature Conservation Baden-Württemberg, 2006) and South Tyrol (Italy; Tasser et al., 2008).

Alternatively, the degree of fragmentation can be expressed as the effective mesh density s_{eff} (i.e. the effective number of patches per 1 000 km² (Jaeger et al., 2007, 2008) which is related to effective mesh size according to $s_{eff} = 1/m_{eff}$ (see Box 2.1). For reading trends off graphs, it is easier to use effective mesh density as increases in s_{eff} indicate increasing landscape fragmentation (Figure 2.5). Therefore, in this report, we mostly present the results using s_{eff}.

We used the Cross-Boundary-Connections procedure (CBC procedure) for calculating the effective mesh size and effective mesh density (see explanation in Annex 2; Moser et al., 2007). This procedure removes any bias due to the boundaries of the reporting units when quantifying landscape structure. It accounts for the connections within unfragmented patches that extend beyond the boundaries of the reporting units.

The probability of successful road crossings and the positive effect of wildlife crossing structures on landscape connectivity can also be included in a more detailed version of the effective mesh size (Jaeger, 2002, 2007). However, the value of effective mesh size would then be species-specific, i.e. the values would differ for different species. Currently, there is a lack of quantitative data about the probability of species to use wildlife crossing structures and the probability of crossing highways successfully which depends on traffic volume on the road. Once such data will be available, these effects can be included in the value of effective mesh size in future studies.

Figure 2.5 Example illustrating the relationship between effective mesh size and effective mesh density



Note: In this hypothetical example, the trend remains constant. A linear rise in effective mesh density (right) corresponds to a 1/x curve in the graph of the effective mesh size (left). A slower increase in fragmentation results in a flatter curve for effective mesh size, and a more rapid increase produces a steeper curve. It is therefore easier to read trends off the graph of effective mesh density (right).

Source: Jaeger et al., 2007.

2.3 Fragmentation geometries, base data and reporting units

To analyse landscape fragmentation, it is first necessary to identify which landscape elements are relevant to fragmentation. The choice of a specific set of fragmenting elements defines a so-called 'fragmentation geometry'. To identify the relative contributions of various types of barriers to the overall fragmentation of the landscape, three different fragmentation geometries (FGs) were used, where each FG handles man-made and natural barriers in a different way (Table 2.1).

Fragmentation geometries A1 and A2 include only man-made barriers: roads, railways, and built-up areas. In many parts of Europe, lakes, rivers and high mountains also play a major role in acting as natural barriers. In some regions, their impact is so important that it is not meaningful to compare the level of landscape fragmentation in such regions with regions without lakes and mountains. Therefore, in geometry B2, lakes, major rivers, and high mountains were considered as barriers, and the level of fragmentation of those parts of these regions was calculated that are covered by land areas that are not high mountains (Map 2.1). Thus, FG-B2 reflects the fact that man-made fragmentation affects biodiversity in combination with natural fragmentation. The resulting values for the fragmentation of non-mountainous land areas can be compared among all regions.

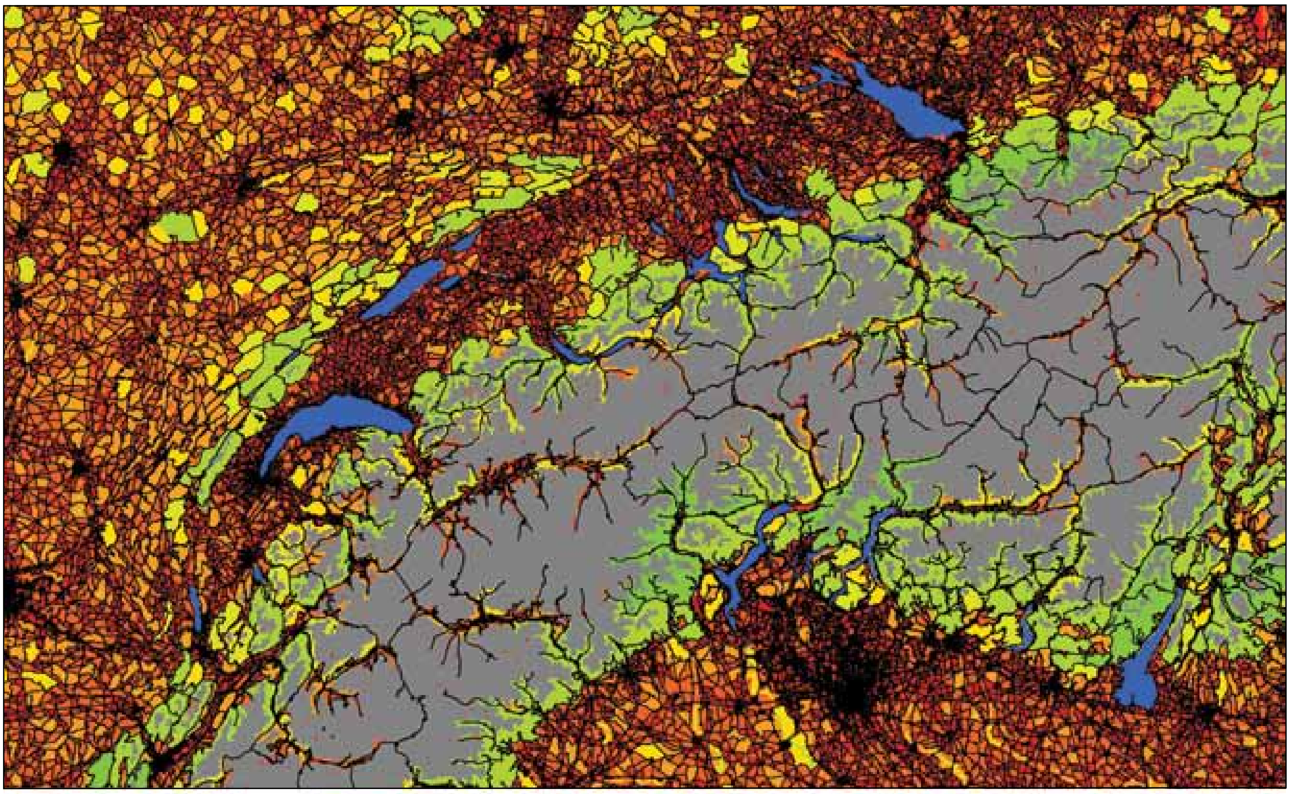
The classification of mountains as barriers depends on the species group studied. Mountains represent habitat and movement corridors for certain species. For such species, FG-A2 may be more appropriate than FG-B2. A similar situation exists for rivers and lakes: they represent movement corridors for certain species and barriers for other species. For species that prefer moving along river banks, keeping river banks free from movement barriers is particularly important.

Clarification was also needed for some other issues. For example, if a road or railway goes through a

Table 2.1 Definition of the three fragmentation geometries used for analysing landscape fragmentation in Europe

		Natural barriers	
		None	Mountains, lakes and major rivers are considered as barriers; the fragmentation of the remaining land area is reported
Man-made barriers (motorways, other roads, railway lines, built-up areas)	Roads up to class 2 (major roads)	**FG-A1:** 'Major anthropogenic fragmentation'	—
	Roads up to class 4 (connecting roads)	**FG-A2:** 'Major and medium anthropogenic fragmentation'	**FG-B2:** 'Fragmentation of non-mountainous land areas'

Map 2.1 Illustration of fragmentation geometry FG-B2 using an example from Switzerland and adjacent countries



Landscape fragmentation in Switzerland and adjacent countries (2009)

Size of remaining patches in km²

- 0–10
- 11–20
- 21–40
- 41–60
- 61–100
- 101–600
- > 600
- Built-up areas
- Lakes
- Mountains
- Roads and railways

0 25 50 100 Km

Note: The barriers are shown in black (built-up areas, roads, railways), and the colours indicate the sizes of the remaining patches in the landscape. Lake Constance and Lake Geneva are visible at the top and on the left of the map, respectively. In FG-B2, the lakes and mountains were considered as barriers, but were not included in the reporting units.

Source: EEA/FOEN, 2011.

tunnel that is longer than 1 km, the landscape in this area was considered as connected and almost not affected by disturbance from traffic noise. However, shorter tunnels were included in the analysis as normal transport routes.

In a related study, an additional fragmentation geometry was used in the calculation of the Landscape-Ecological Potential (LEP), which is an indicator to measure and assess terrestrial ecosystem integrity at large scales in Europe as a prerequisite for ecosystems to deliver multiple services (Weber et al., 2008). As this fragmentation geometry included roads of classes 00 to 03 it would be roughly located between FG-A1 and FG-A2 (urban areas were delineated according to the concept of Urban Morphological Zones).

Every fragmentation geometry has its strengths and weaknesses. The choice of the most appropriate FG depends on a study's objectives and context. This condensed report mostly shows the results for FG-B2 because it is the most suitable one for comparing different regions. For a more detailed analysis of landscape fragmentation in the context of environmental impact assessment, cumulative impact assessment, and strategic environmental assessment, a combination of all three (or even more) FGs may be more appropriate than any single FG.

The analysis used the 2006 Corine Land Cover (CLC) for the built-up areas at a scale of 1:100 000 (minimum mapped unit size of 25 ha). For the linear features, we used the 2009 TeleAtlas dataset (Table 2.2). TeleAtlas is a provider of digital maps for navigation services, covering 200 countries around the world. The classification of roads was based on the road classes used in the TeleAtlas Multinet® platform (scale 1:100 000). The TeleAtlas dataset is currently the only available dataset of road classes that is consistent across Europe. These maps are highly accurate and provide standardised cover for 28 countries in Europe, and therefore, the results also have a similar level of accuracy. The roads were buffered (on either side) to reflect the loss of habitat due to their surface. We had also intended to use the TeleAtlas of 2002 in combination with the Corine Land Cover of 2000 to investigate landscape fragmentation for an earlier point in time and determine the direction and rate of change in landscape fragmentation. However, it turned out that the TeleAtlas data for 2002 and 2009 were not comparable because of various changes in road classes between the two points in time. In addition, there was a concern about the quality of the data for Romania in the year 2009: Not all roads of classes 3 and 4 in Romania seemed to be represented in the TeleAtlas dataset. Therefore, our calculations of the degree of landscape fragmentation for Romania for FG-A2 and B2 underestimated the true level of fragmentation.

Table 2.2 Datasets and fragmenting elements used to create the fragmentation geometries

Dataset	Year	Fragmenting elements
Corine Land Cover (CLC)	2006	1.1: Continuous urban fabric, discontinuous urban fabric
		1.2: Industrial and commercial units, road and rail networks and associated land, port areas, and airports
		1.3: Mineral extraction sites, dump sites, and construction sites
		1.4.1: Green urban areas
		1.4.2: Sport and leisure facilities (only included as a barrier if they were completely surrounded by the previous classes)
		4.2.2: Salines
		5.1.2: Water bodies
TeleAtlas Multinet®	2009	Class 00 'Motorways' (buffer 2 × 15 m)
		Class 01 'Major roads' (buffer 2 × 10 m)
		Class 02 'Other major roads' (buffer 2 × 7.5 m)
		Class 03 'Secondary roads' (buffer 2 × 5 m)
		Class 04 'Local connecting roads' (buffer 2 × 2.5 m)
		Railroads (buffer 2 × 2 m)
Nordregio	2004	Criterion 1: Elevation is higher than 2 500 m
		Criterion 2: Elevation is higher than 1 500 m and the slope is steeper than 2 °
WorldClim	2009	Mean July temperature < 9.5 °C (mean 1950–2000, 30 '')
CCM2: Catchment Characterisation and Modelling version 2.1	2007	Catchment areas greater than 3 000 km^2

Given that the mountain ranges in Europe exhibit a large variation in altitude and latitude (snow levels in Nordic regions start at lower altitudes), an appropriate classification of the mountains of Europe was needed (Pecher et al., 2011). We considered as high mountains all elevations above 2 500 m and also those elevations above 1 500 m that had a slope of more than 2 degrees (criteria 1 and 2 according to the European Commission). In addition, we used the 9.5 °C isoline for identifying mountainous areas, which mostly applies in Scandinavia following the rationale that the growing season is very short in areas with temperatures lower than this isoline, primary production is very limited (no trees, and presence of glaciers), and that these regions have limited accessibility for humans (virtually no construction of buildings, towns or roads). An additional rationale is that these mountainous areas are not suitable for settlement and usually have no or very few roads. Therefore, they should be removed from the reporting units before comparing regions with differing amounts of such areas for the comparison to be meaningful. Otherwise, their comparison would not make much sense.

Only rivers with catchment areas greater than 3 000 km^2 were included as fragmenting elements because such water bodies tend to be navigable and thus become a relevant obstacle for the free movement of many terrestrial animals. We used the CCM2 (Catchment Characterisation and Modelling version 2.1) river and catchment data for Europe (Vogt et al., 2007), as data about river width were not available. For the lakes, we used the Corine Land Cover (CLC) classification and selected the class 5.1.2 (water bodies). More detailed information about the data sources used is given in the final report of the Landscape Fragmentation in Europe project (Madriñán et al., 2011).

As a consequence of the resolution of the CLC data with a minimum mapping unit of 25 ha, the evaluation of the results in terms of fragmentation effects for species that are sensitive to habitats smaller than 25 ha is limited. Such species which are still important in food chains and for certain ecosystem services may also be affected by fragmentation processes at smaller scales. For example, to capture low-density sprawl in units < 10 ha, data at a higher resolution would be required (which is not available at the European scale). The 25 ha resolution is appropriate for quantifying the degree of fragmentation at the scale of a 1 km^2 grid and for larger reporting units. However, for traffic planning at the regional scale, additional, more detailed information will be needed along with information about intensive agriculture, intensive silviculture, mining activities, etc.

It would be interesting to include additional fragmenting elements in the landscape, such as intensively used agricultural fields (e.g. Girvetz et al., 2008). However, it is difficult to find a consistent dataset about intensively used agricultural fields on the European scale. These should be considered in a future project. The fragmentation of particular types of ecosystems would also be of interest, e.g. fragmentation of forests (Kupfer, 2006; Fischer and Lindenmayer, 2007; Saura et al., 2011) or fragmentation of grasslands (Gauthier and Wiken, 2003) by all other land cover types. This would require the use of different fragmentation geometries, according to the ecosystem type considered. Our current study has a focus on landscape fragmentation by the man-made and natural barriers listed in Table 2.1.

This study used three types of reporting units for which fragmentation was calculated and reported. The available data resulted in the following set of regions for the fragmentation analysis:

1. 28 countries in Europe,

2. 580 NUTS-X regions,

3. 1 km^2 grid units within the 28 countries.

The NUTS-X regions refer to administrative units of the European Union (NUTS = Nomenclature of Territorial Units for Statistics). NUTS is a hierarchical classification that subdivides each Member State into a whole number of NUTS-1 regions, each of which is in turn subdivided into a whole number of NUTS-2 regions, and so on for NUTS-3, -4 and -5 levels. The NUTS-X layer is a combination of the NUTS-2 and NUTS-3 layers to create reference regions that are more homogenous in size than the other two. NUTS-X regions are a synthesis of NUTS 2 and 3 regions that provide region-specific information on rurality, urban structure, socioeconomic profiles and landscape character.

The 1 km^2 grid was used to describe fine detail fragmentation patterns in our study. This grid is the reference grid used for EEA activities in the frame of Land and Ecosystem Accounting (LEAC).

The main focus of this analysis was on the NUTS-X regions because they are more similar in size than the 28 countries and because there is enough information available for meaningful statistical analysis. Similar size of the reporting units is important for meaningful statistical analysis because each reporting unit is represented by one data point and all data points have equal weight in the analysis.

2.4 Predictive models for landscape fragmentation based on geophysical and socioeconomic characteristics

In order to examine how strongly socioeconomic and geophysical parameters are related to fragmentation values, a set of independent variables was selected for their potential importance as drivers of landscape fragmentation and for their availability at the European level. A consistent finding of published studies about landscape fragmentation that include socioeconomic information is that the extent and pace of land-cover change is often inversely related to distance to urban centers (LaGro and DeGloria, 1992; Turner et al., 1996). These studies report a general tendency that landscape fragmentation is highest near to the urban centres and much lower in areas distant from cities. Nevertheless, several other factors are also known to create fragmentation patterns in the landscape that are not necessarily related to urban centres alone, and that socioeconomic characteristics differ markedly among urban centers that define the fragmentation patterns around them.

The variables used in this study can help identify the main driving forces (demographic and economic) of landscape fragmentation in Europe, as driving forces and the resulting levels of landscape fragmentation would be expected to co-vary. Accordingly, the predictor variables can also be used as an early warning system in which the increase or decrease of the value of some variables (e.g. in population density or GDP) by a given amount may suggest an increase in fragmentation in the near future (Table 2.3).

Our general hypothesis was that a region is likely to be more fragmented than other regions if it has a high population density (i.e. regions with higher population density tend to be more fragmented), high gross domestic product per capita (i.e. regions with higher GDP per capita tend to be more fragmented), low unemployment rate (lower fragmentation in regions with higher unemployment rate), high volumes of goods and passengers transported (i.e. regions that load and unload a higher volume of freight and transport more passengers than other regions tend to be more fragmented), with a population that is well educated (higher levels of fragmentation in regions with higher expenditure on education, as people pursue more interests and more activities, e.g. travel more) and environmentally aware (i.e. regions with higher expenditure in environmental issues tend to be more fragmented than other regions), with few natural barriers (few high mountains or large lakes), and with a small Island size Index (higher fragmentation in smaller islands). The influence of hills (areas at low elevations with gentle slopes, but not lowland) was relevant only in the Mediterranean countries: Regions with higher proportions of hills were expected to be more fragmented, because these areas were suitable for human settlement (in other regions of Europe, larger areas of lowland are present, and the influence of hills is low).

$$s_{eff} = PD + GDPc + UR + QGLUc + VPD + EEc + EDc + MtSl + Hills + IsI$$

In words:

s_{eff} = Population + Economy + Transport + Education and environment + Geophysical variables

Various additional explanatory variables would have been of interest for predicting the degree of landscape fragmentation in Europe, e.g. commuter volumes and distances, amount of forest cover in each region, remoteness, and nearness to the coast, policies and prevalence of planning concepts, soil quality, geological characteristics, climate, and amount of transfer payments for high-class infrastructure projects. However, these variables were not included because the available data for many of these variables are difficult to find at the European scale in good resolution, or are only available at the national level for some countries. The source of all socioeconomic data was Eurostat (http://nui.epp.eurostat.ec.europa.eu/).

To examine how the socioeconomic parameters are related to fragmentation levels, we used generalised linear models (GLM), as illustrated in Figure A3.1 in Annex 3. A global linear regression model was developed containing all the physical and socioeconomic variables. Model selection was done by successively adding variables and factors for which we had a working hypothesis. All possible combinations of the explanatory variables were examined (for further information about the statistical analysis, see Annex 3). This analysis was performed first for all NUTS-X regions in the 28 investigated countries together. Subsequently,

Table 2.3 Physical and socioeconomic variables used in the 2009 analysis

Variable	Source	Complete cases	Unit
Population density (*PD*)	NUTS	498	number of inhabitants per km²
GDP per capita (*GDPc*)	NUTS	481	Euros PPs per person in 2007
Quantity of goods loaded and unloaded per capita (*QGLUc*)	NUTS	418	1 000 tons loaded and unloaded per person
Volume of passenger transport density (*VPD*)	Country	487	1 000 pkm per km²
Environmental expenditure (*EEc*)	Country	494	Euros PPs per person
Unemployment rate (*UR*)	NUTS	504	% of active population in 2007
Education, per capita (*EDc*)	Country	500	Euros PPs per person in 2007
Island size Index (*IsI*)	NUTS	530	no unit (0 < *IsI* < 1)
Hills-% (*Hills*)	NUTS	530	%
Mountain-and-slope-% (*MtSl*)	NUTS	530	%

Note: The three variables *IsI*, *Hills* and *MtSl* are available for all of Europe. However, some countries were not included in the socioeconomic analysis because of lack of data (Sweden, Bulgaria and San Marino). Without them, the highest number of cases possible for the socioeconomic models was 530.

The unit Euro PPs (PPs = purchasing power standards) indicates that the variable was adjusted for differences in price levels between the countries.

Source: EEA/FOEN, 2011.

we repeated the analysis for six groups of NUTS-X regions (see Section 3.2.2). In each one of these subgroups, we ran our GLM models to determine the principal drivers of landscape fragmentation. Finally we used the most parsimonious model in each group of regions to develop a map of observed vs. predicted fragmentation levels.

3 Landscape fragmentation in Europe

3.1 Current degree of landscape fragmentation in Europe

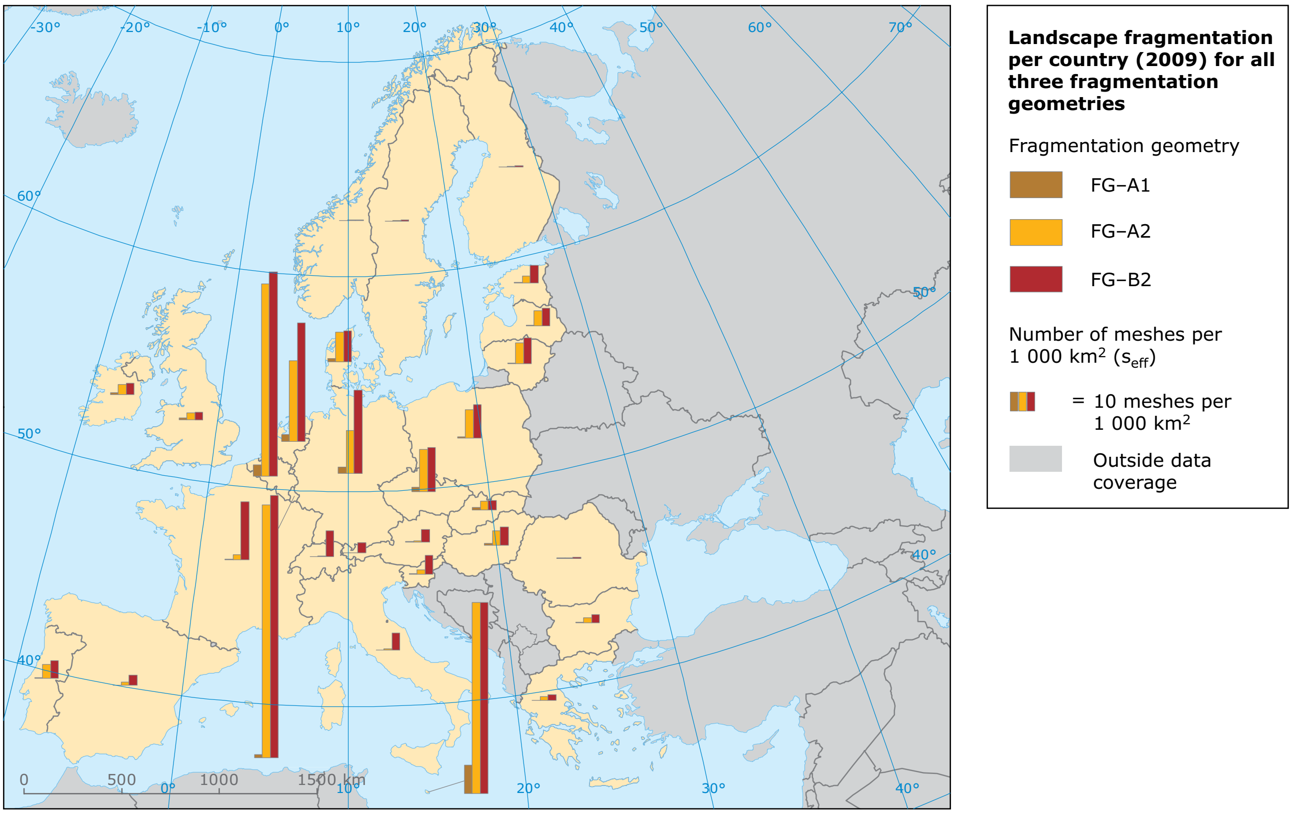
This chapter presents the results of the fragmentation analysis for fragmentation geometry B2 'Fragmentation of Non-Mountainous Land Areas' for 2009 on three scales: countries (Section 3.1.1), 1-km² grid (Section 3.1.2), and NUTS-X regions (Section 3.1.3). A more detailed presentation of the results that includes FG-A1 and FG-A2 is given in the final report of the Landscape Fragmentation in Europe project (Madriñán et al., 2011).

3.1.1 *Landscape fragmentation in the countries*

The effective mesh density values cover a large range from low values in the Iberian and Scandinavian peninsulas, to very high values in the Benelux countries and Germany (Map 3.1). The values in the Scandinavian countries are so low that the corresponding bars in Map 3.1 are barely visible. Large parts of Europe are highly fragmented by transportation infrastructure and urban development. High fragmentation values are often found in the vicinity of large urban centres and along major transportation corridors. The value of the effective mesh density for all 28 investigated countries together is s_{eff} = 1.749 meshes per 1 000 km².

The Benelux countries are clearly the most fragmented part in Europe (s_{eff} > 60 meshes per 1 000 km²), with one of the highest population densities in the world and a very dense road

Map 3.1 Landscape fragmentation per country for all three fragmentation geometries



Source: EEA/FOEN, 2011.

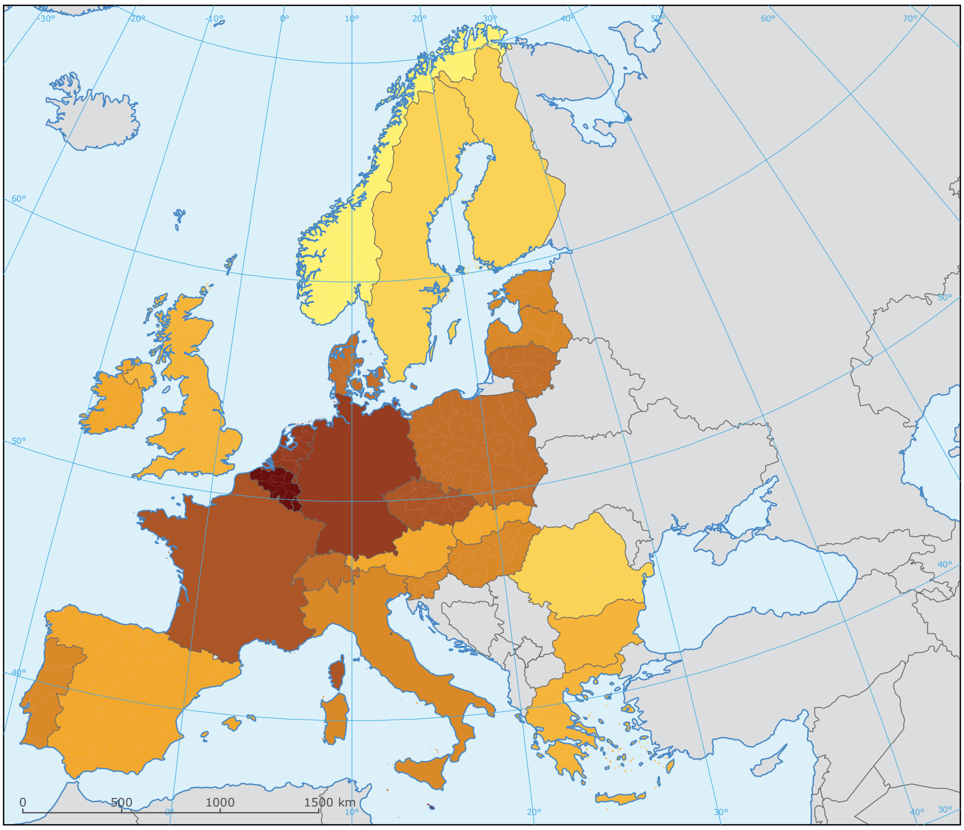
network (Map 3.2 and Figure 3.1). Further infrastructure development is expected and will probably be the most important cause of destruction of the remaining natural habitats in these countries. In part, this development is due to this area's role as a crossroad region in the European context (Froment and Wildman, 1987).

Belgium and the Netherlands have followed two different types of urban development, even though they both have high population densities. Belgium has a high urbanisation level of 97.3 % and an average population density of 330 inhabitants per km^2 (Antrop, 2004). The Netherlands, which has an urbanisation level of 83 % and a population density of 399 inhabitants per km^2 (CIA Factbook, 2010) most noticeably has a polycentric urban structure in the Randstad region that exhibits some concentration of the population in urban centres at a national level. This is in clear contrast with Belgium which exhibits a disperse urbanisation pattern due to continuous increase of smaller urban centres in the countryside (Nijkamp and Goede, 2002).

Following the Benelux countries, Germany is one of the most heavily fragmented countries in Europe in all three fragmentation geometries (Figure 3.1). This country has a long history of road and motorway construction. Today, Germany's motorway network has a total length of 12 813 km (Deutscher Bundestag, 2011). It is one of the most closely meshed motorway networks in the world and exhibits one of the highest volumes of passenger and freight transport in Europe. Its central location in Europe, high levels of industrialisation, and the lack of major topographical obstacles against the construction of transportation infrastructure explain this high level of landscape fragmentation, among other factors.

The next most heavily fragmented country is France (Figure 3.1). France exhibits a wide range of fragmentation patterns. The country includes some of the most heavily fragmented regions in Europe. The northern part of the country (e.g. around the metropolitan area of Paris) has similar fragmentation levels as the neighbouring

Map 3.2 Landscape fragmentation per country in 2009



Landscape fragmentation per country (2009)

Number of meshes per 1 000 km^2 (s_{eff})

- < 0.1
- 0.1–0.5
- 0.6–1.0
- 1.1–2.0
- 2.1–4.0
- 4.1–7.0
- 7.1–10.0
- 10.1–20.0
- 20.1–35.0
- 35.1–75.0
- 75.1–100.0
- > 100
- Outside data coverage

Note: Landscape fragmentation was calculated using fragmentation geometry FG-B2.

Source: EEA/FOEN, 2011.

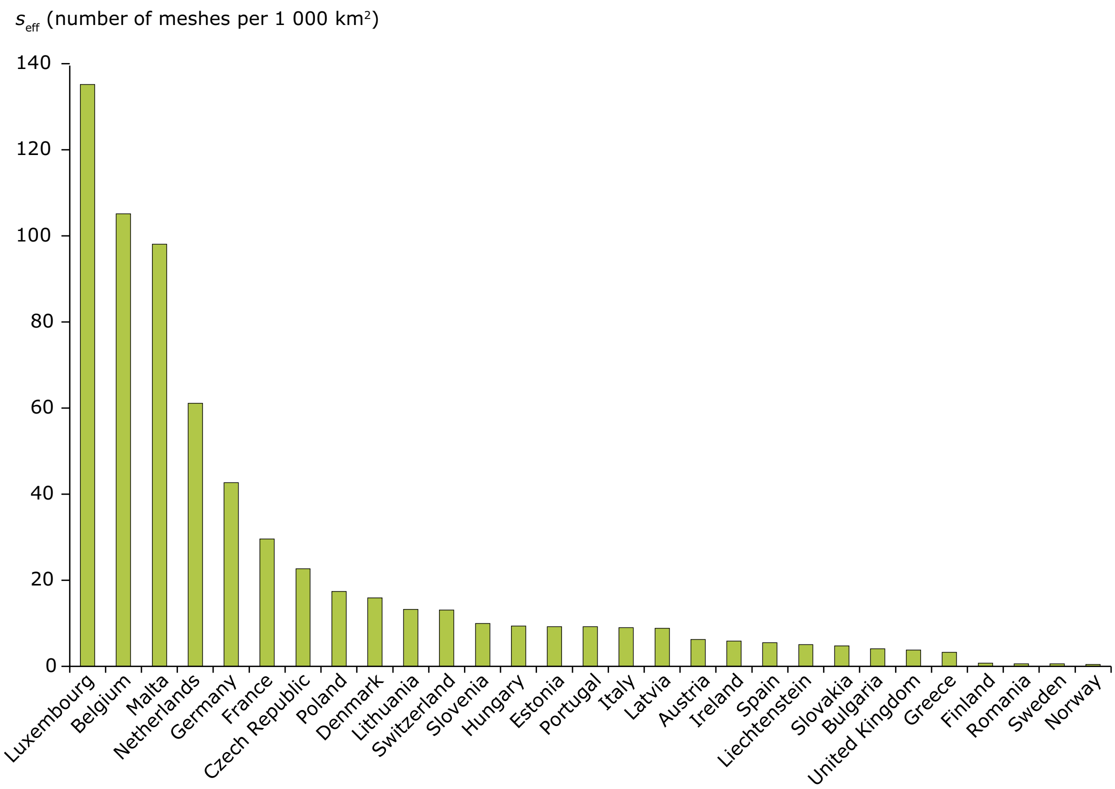
countries of Belgium, the Netherlands and Germany, and similar to them, has large areas of intensive agriculture and no mountains. In contrast, the fragmentation levels in the southern, more mountainous part of the country are more similar to those of Spain and Italy.

Following France, the Czech Republic and Poland rank fifth and sixth among the 28 countries investigated. The topographical conditions in these countries are similar to Germany. However, major differences exist between their economic development since the middle of the last century. In addition, Poland's population density is lower. Nevertheless, quite similar to Germany, high fragmentation values are observed in both countries.

The countries that are strongly influenced by the Alps, like Switzerland and Austria, exhibit some of the lowest effective mesh density values in Europe for both FG-A1 and FG-A2, even lower than in Norway. However, once the Alps are considered as barriers and removed from the reporting units in FG-B2, the fragmentation value for Austria places the country at rank 18 (at a similar level as Latvia and Ireland), while Switzerland is placed at rank 11 (at the same level as Denmark or Lithuania). Not surprisingly, most of the fragmentation is in lowlands and in the valley floors of the rivers. Here, the extent of fragmentation is much greater than indicated by the calculated average figures (Jaeger et al., 2007, 2008).

In the Mediterranean countries, urbanisation patterns have been influenced by the attractive climate and the topography of the landscape. In this area, being the world's most important touristic destination, the process of urbanisation takes place close to the coastal areas and around major urban centres. Most of the road construction and road improvements have been conducted close to the coast while the interior areas have significantly fewer roads (Nijkamp and Goede, 2002). In Spain and Italy, the spatial pattern of employment has continued to focus on the metropolitan areas. In Spain, the big cities are still attracting people and continue to grow, but in Italy, the population of the central cities has begun to decline or become stagnant (Graeme et al., 2003). In the particular case of the Iberian Peninsula, the fragmentation values are the highest along the coast, most pronounced in Portugal and north-eastern Spain. The fragmentation pattern on the peninsula is clearly

Figure 3.1 Bar diagram of effective mesh density values per country for FG-B2 in 2009



Source: EEA/FOEN, 2011.

separated from the fragmentation pattern in France by the Pyrenees.

The United Kingdom is ranked between Bulgaria and Greece and exhibits a large range of fragmentation values, including two of the most fragmented regions in the continent (inner and outer London) and also very low levels of fragmentation in the highlands and north-eastern Scotland. The United Kingdom provides a good example of the development of fragmentation patterns progressing from urban centres. The country followed the 'physical agglomeration' principle, since early in the 20th century already 78 % of the country's population lived in urban centres (Champion, 2008). By the year 2000, this proportion had reached 89 %. The United Kingdom is less fragmented than many other countries such as Germany and France. However, very high fragmentation levels occur around the major urban centres with high population densities and in some of the regions between these centres.

Romania is an interesting case by itself. It is the largest country in south-eastern Europe. According to the TeleAtlas dataset, its fragmentation levels are similar to the ones in the Scandinavian or alpine countries ([1]). The Carpathian Mountains dominate central Romania. These mountain ranges (14 in total) reach up to 2 000 m on average only, but some of these mountain ranges (e.g. Fagaras and Retezat) exceed 2 500 m. Today, Romania has 13 national parks and more than 500 protected areas. The Romanian Carpathian Mountains are home to 60 % of Europe's bears, 40 % of Europe's wolves and 35 % of its lynx. Therefore, Romania has an important role for biodiversity in Europe. These protective measures have sustained a landscape with low fragmentation levels. However, this situation presents a great challenge for the future: the question is how the large unfragmented areas of the country that are important for biodiversity can be effectively protected as there is a strong pressure for improving and extending the existing road network.

Norway is the least fragmented country in Europe. It is sparsely populated, and most of the population is concentrated around Oslo, Bergen, Trondheim and Stavanger as a large part of the country is inhospitable for agriculture and permanent settlement (areas at higher elevation with long winters). Accordingly, most parts of the country have low fragmentation values, even though its population has a very high GDP per capita. Finland is much less mountainous than Norway but still has low levels of fragmentation (ranking fourth to fifth last among the 28 countries in all FGs). The degree of fragmentation decreases from south to north, related to less favourable climatic conditions and lower population densities.

The rather small islands of Malta are very highly fragmented. Malta has a very high population density. The largest possible value of effective mesh size for Malta is its island size (313 km^2), and accordingly, the lowest possible value of the effective mesh density is 3.2 meshes per 1 000 km^2. Roads and urbanisation areas cover large parts of the main island and contribute to the high s_{eff} value.

Many fragmentation patterns and explanations as in the countries discussed above also apply to the other eight countries (Denmark, Estonia, Hungary, Ireland, Latvia, Lithuania, Slovakia and Slovenia).

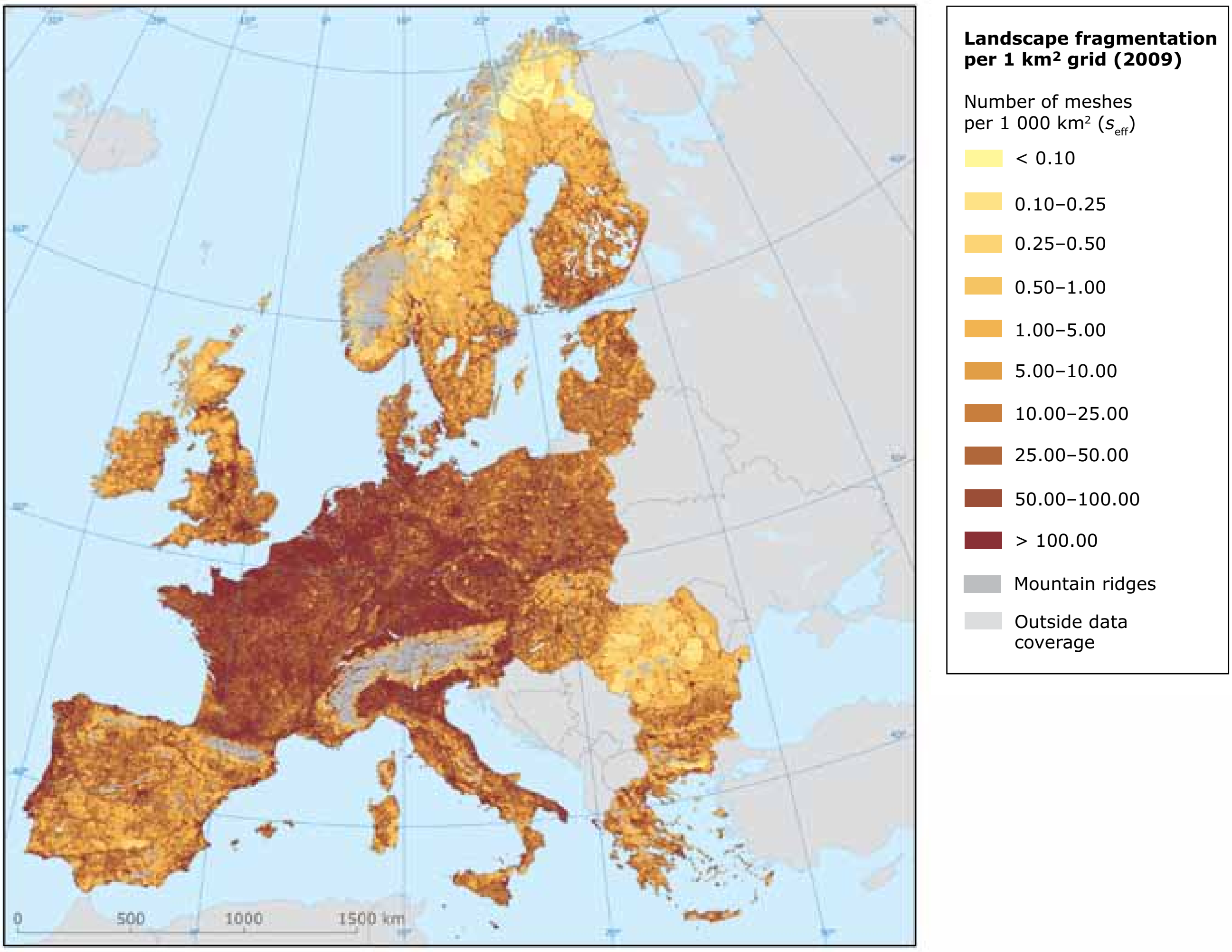
3.1.2 Landscape fragmentation at 1 km^2 resolution

This section presents the patterns of fragmentation in the 28 countries investigated based on a grid of cells size of 1 km^2 (Map 3.3). At the outer boundaries of Europe, fragmentation levels are lower than in the central part. This is true for all three FGs. These areas include Scandinavia, eastern European countries, Mediterranean countries, Ireland and Scotland. An exception to this general pattern is the western part of Portugal which is more fragmented. Southern Europe is more fragmented than northern Europe, but not as much as the central area of Europe. In the central part of Europe, the major transportation corridors and the neighbouring areas are highly fragmented, including areas of high urban sprawl.

Most of western and central Europe is heavily fragmented, with values ranging between 35 to 100 meshes per 1 000 km^2. The coastal areas of the Iberian and Italic peninsulas and most of England are also in this category of high fragmentation. The regions with very low fragmentation values are located in the northern regions of the Scandinavian countries and in Romania with less than 0.1 meshes per 1 000 km^2. The mountain ranges are surrounded by areas with rather low levels of fragmentation (0.5 to 2 meshes per 1 000 km^2).

([1]) However, not all roads of classes 3 and 4 seem to be represented in the TeleAtlas dataset, even though the TeleAtlas documentation lists Romania as 100 % complete. Therefore, our calculations of the level of fragmentation for Romania may underestimate the true levels of fragmentation in this country.

Map 3.3 Landscape fragmentation per 1 km² grid in 2009



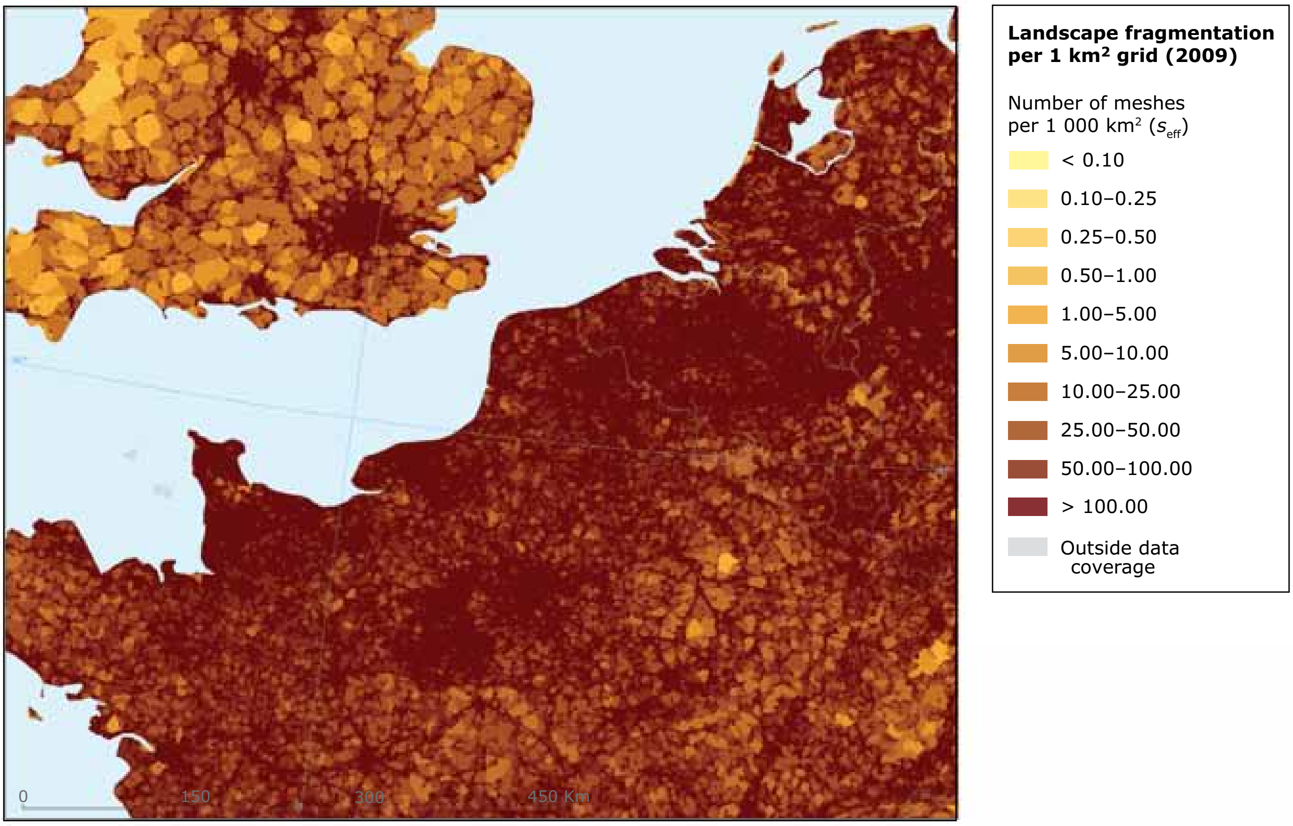
Note: Landscape fragmentation was calculated using fragmentation geometry FG-B2.

Source: EEA/FOEN, 2011.

Accordingly, the Alps, the Pyrenees, and the Scandinavian mountain ranges are clearly visible as the least fragmented parts in Europe. In contrast, the Apennines are visible in FG-A1 as they have lower levels of fragmentation, but they differ less strongly from the rest of the landscape in FG-A2 and FG-B2. A similar observation is also made for the mountains in Greece, the Carpathians and the Balkan mountain range.

We present two regions in higher resolution to allow the reader to visually compare the regions and distinguish more detail. The first region shows the Channel (Map 3.4) and the focus of the second region is on the Alps (Map 3.5). The mountains and lakes in the region including the Alps were considered as barriers and excluded from the reporting units (i.e. the cells of the 1 km² grid). It is clearly visible that there are almost no areas of low fragmentation left in Belgium, the Netherlands and northern France, like islands in an ocean of highly fragmented landscape. This has serious consequences for biodiversity and landscape quality. The location of northern France in Europe with Paris as the important centre, high level of industrialisation and intensive agriculture explain the very high level of landscape fragmentation in this part of France. In contrast, there still are various unfragmented patches of significant size in the western parts of the United Kingdom (Map 3.4). Areas of low fragmentation surround the Alps or are associated with other regions of higher elevation, for example, in the Black Forest (Germany) and in the Apennines (Italy) (Map 3.5).

Map 3.4 Landscape fragmentation per 1 km² grid in the Channel region in 2009



Note: Landscape fragmentation was calculated using fragmentation geometry FG-B2.

Source: EEA/FOEN, 2011.

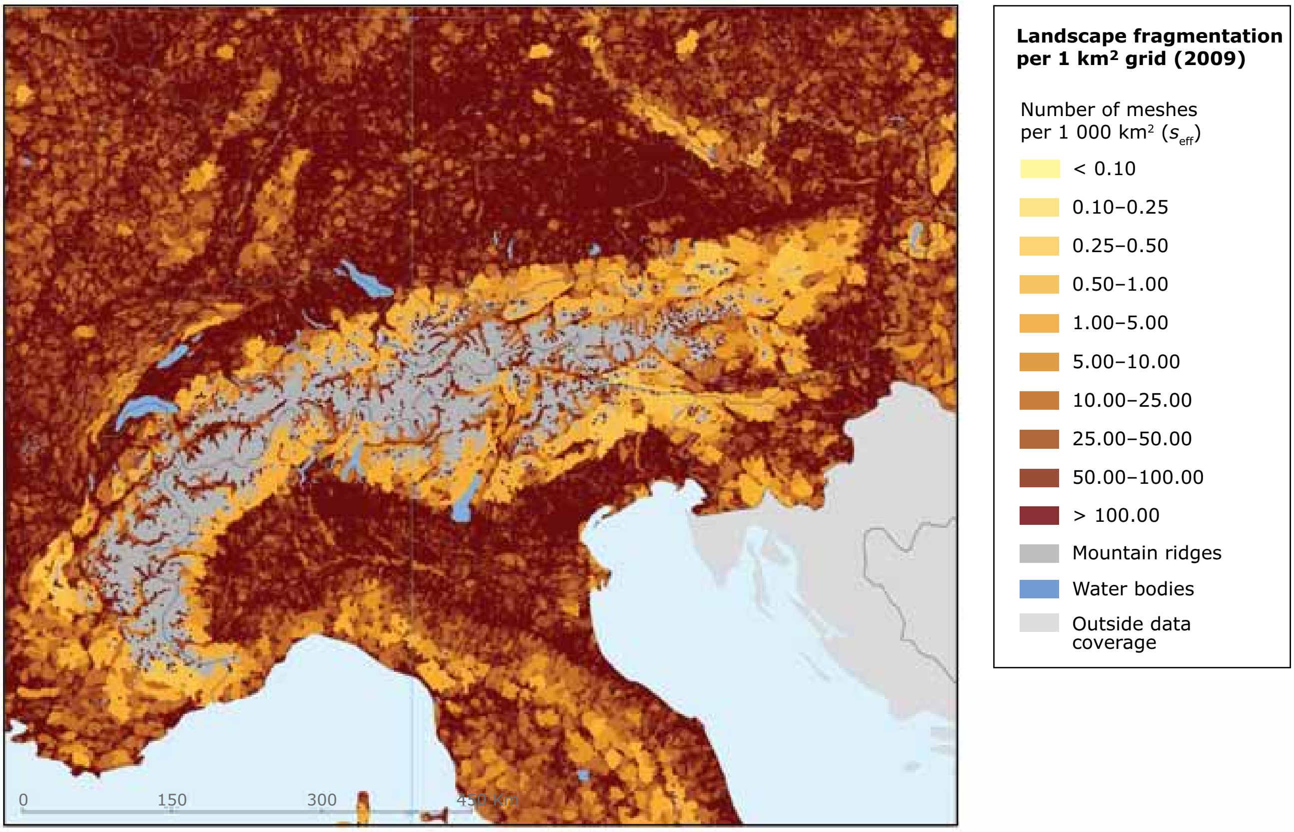
3.1.3 Landscape fragmentation in the NUTS-X regions

The analysis of the NUTS-X regions confirmed that the most fragmented NUTS-X regions (> 50 meshes per 1 000 km²) are located in Belgium, the Netherlands, Luxembourg, France, Germany, Denmark, the Czech Republic, Poland, the United Kingdom and Slovenia (Map 3.6). Some of them have effective mesh densities even above 100 meshes per 1 000 km². The NUTS-X regions in Norway, Sweden, Finland and Romania are among the least fragmented.

Map 3.6 and Figure 3.2 show the distribution of the fragmentation values within the 28 countries investigated. In some countries, only a small proportion of NUTS-X regions is highly fragmented, e.g. in Ireland and Greece, whereas in other countries a much larger proportion is highly fragmented, e.g. in Germany. The most fragmented NUTS-X regions in Europe are metropolitan Paris (FR101, FR105, FR106), inner London (UKI1), Brussels (BE10), and Vatican City (VC) with more than 1 000 meshes per 1 000 km²; Copenhagen (DK001), Val-de-Marne (FR107), Berlin (DE30), West Midlands (UKG3), and Vlaams-Brabant (BE24) with more than 300 meshes per 1 000 km²; and the regions of outer London (UKI2), Bucharest (RO081) and Budapest (HU101) with more than 275 meshes per 1 000 km². The least fragmented regions are Finnmark (NO073), Lappi (FI1A3), Vrancea (RO026), Troms (NO072), Jämtlands län (SE072), Norrbottens län (SE082), Nord-Trøndelag (NO062), Covasna (RO073), Nordland (NO071) and Buzau (RO022) all with less than 0.34 meshes per 1 000 km². Many of these regions are located in Norway or Romania.

There is a clear difference in the levels of fragmentation between eastern and western Germany. This indicates opportunities for protecting biodiversity by conserving the remaining relatively large unfragmented areas. In contrast, no such difference is apparent in FG-A1. After the reunification of Germany in 1990, significant amounts of money were invested in the extension of

Map 3.5 Landscape fragmentation per 1 km² grid in the region around the Alps in 2009



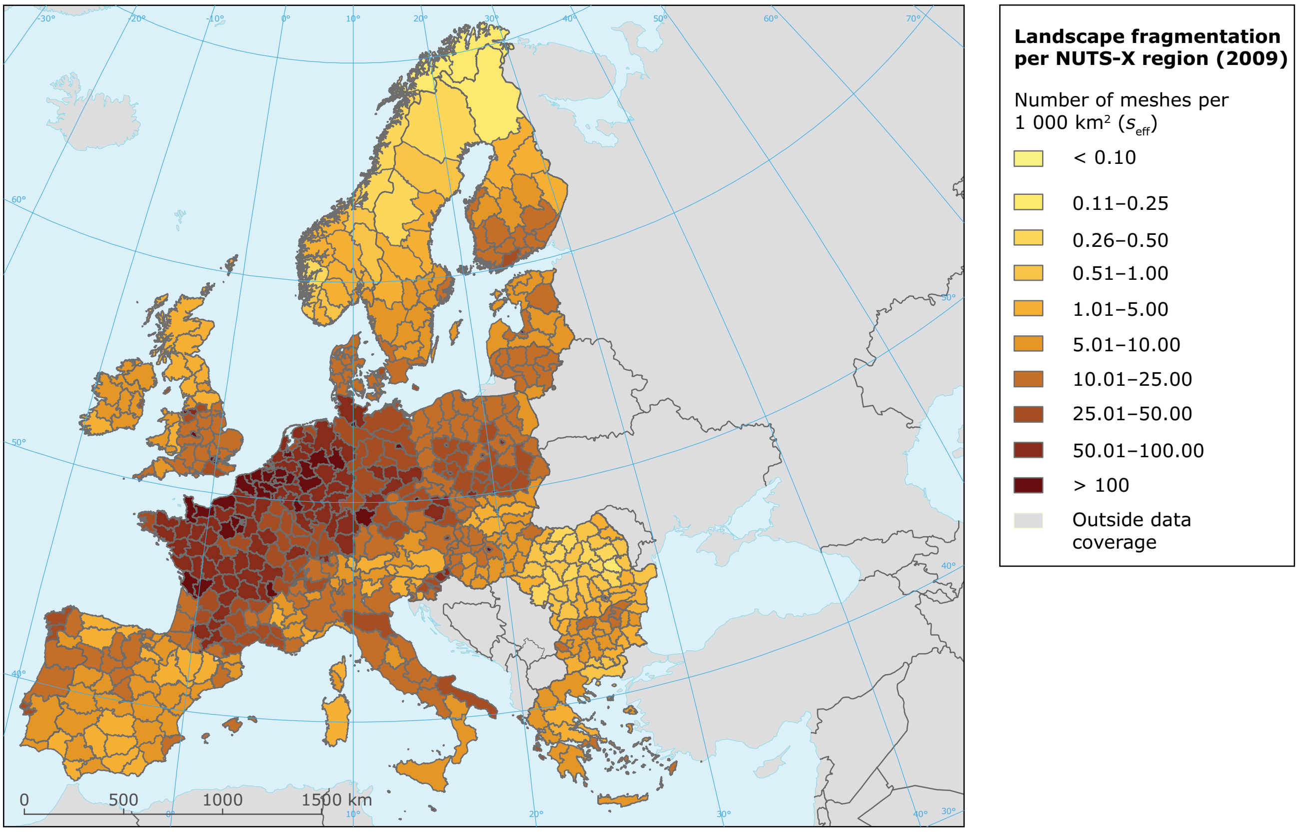
Note: Landscape fragmentation was calculated using fragmentation geometry FG-B2.

Source: EEA/FOEN, 2011.

their national road network which is most relevant on the level of fragmentation in FG-A1. This levelled off the differences between eastern and western Germany in this fragmentation geometry.

Switzerland has been considered one of the leading countries in the world in promoting a more sustainable use of the landscape, with a strong legislation that limits the amount of roads to be constructed. By the year 2010, 93 % of the motorways that are included in the national transportation plan of the country had already been built (Galliker, 2009). In a referendum held in 1994, Swiss voters rejected a plan to increase the road capacities in sensitive areas of the Alps (Bundesverfassung der Schweizerischen Eidgenossenschaft, 1999, Art. 84 Alpenquerender Transitverkehr). According to international agreements with the European Union, no more roads will be constructed to cross the Alps and most freight transport crossing the Alps is limited to using the railway connections through the tunnels of Gotthard and Lötschberg. The strict protection of the forest area since 1902 is noteworthy in this context as well. The level of protection of the agricultural areas is much less effective. More than two thirds of the Swiss population lives in cities and large agglomerations. However, urban sprawl is progressing rapidly in the Swiss Lowlands and in the valley floors of the Alpine rivers (Schwick et al., 2011), causing the destruction of valuable agricultural soils. Many landscape alterations during the last 50 years have contributed to the reduction in the diversity of landscape elements, affecting outdoor recreation, the beauty of the landscape, and the overall quality of life (Ewald and Klaus, 2009).

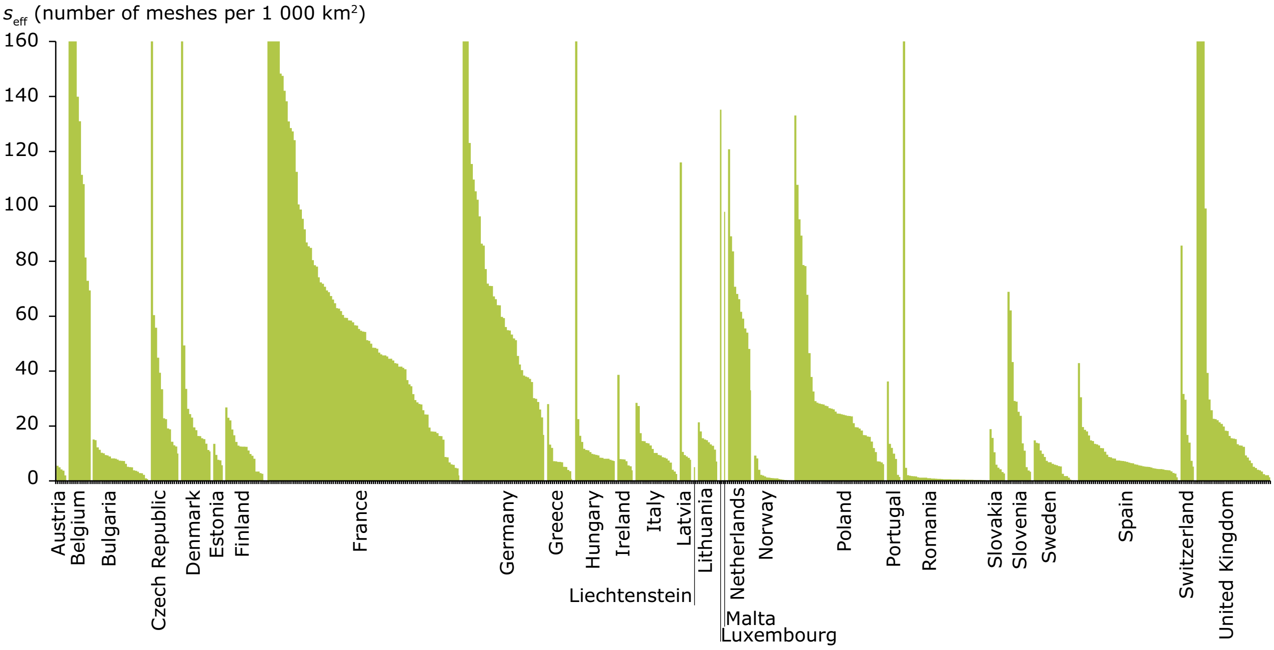
Map 3.6 Landscape fragmentation in NUTS-X regions in 2009



Note: Landscape fragmentation was calculated using fragmentation geometry FG-B2.

Source: EEA/FOEN, 2011.

Figure 3.2 Bar diagram of effective mesh density values per NUTS-X region for FG-B2 in 2009



Note: NUTS-X regions grouped per country (Liechtenstein included).

Source: EEA/FOEN, 2011.

3.2 Predictive socioeconomic models

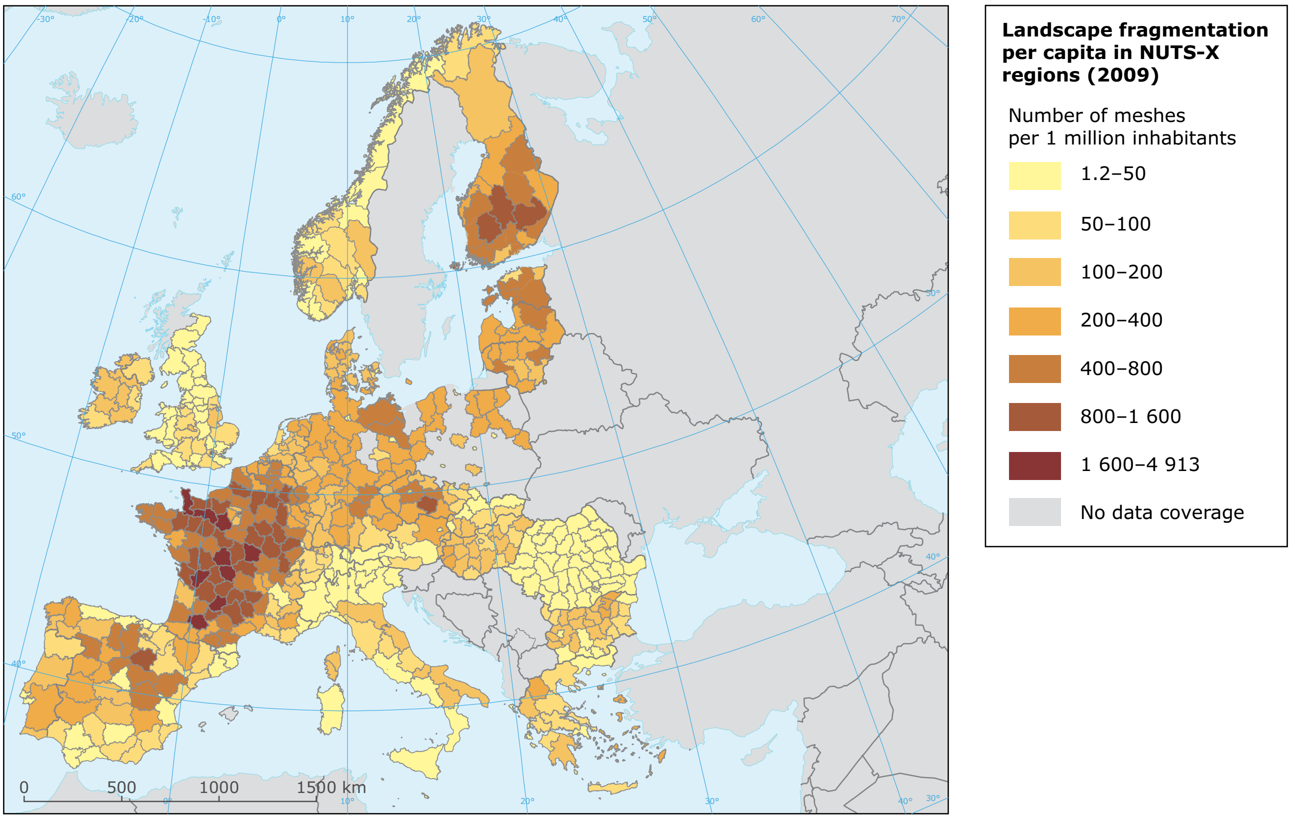
This section compares two approaches for predicting levels of fragmentation based on socioeconomic variables. The results show that the pan-European model presented first (Section 3.2.1) is limited in its predictive value. Predicting landscape fragmentation based on a combination of six models (one for each of six large regions in Europe) is much more appropriate and more relevant (Section 3.2.2).

3.2.1 A pan-European model explaining landscape fragmentation at the continental scale

Fragmentation geometry B2 is the most important fragmentation geometry as it is possible to compare regions with differing geophysical conditions, i.e. percentage of area covered by mountains or lakes as these areas were excluded from the reporting units. In addition, this fragmentation geometry includes the most relevant barriers (not just the three highest road classes). For these reasons, we used this fragmentation geometry to conduct our socioeconomic analysis.

The simplest approach that can be used to relate landscape fragmentation to a socioeconomic variable is to study the ratio of the degree of landscape fragmentation to the value of the socioeconomic variable. An example is the ratio of effective mesh density to population density (unit: effective number of meshes per capita). This approach accepts that regions with higher population density will be more fragmented. The resulting map shows that in many sparsely populated regions, landscape fragmentation per capita is quite high, i.e. higher than in urbanised regions, but not always (Map 3.7). Even though this approach is very rough, some general patterns can be identified and compared with the results from the full statistical models (Maps 3.8 and 3.10). In regions where fragmentation is high and population density is rather low, the resulting values are high. In regions where both fragmentation and population density are high (or both are low), similar values of the ratio result. In regions with low levels of fragmentation and rather high population density, the resulting values are low. Most countries exhibit a mixture of higher and lower values, dominated by medium values

Map 3.7 Landscape fragmentation per capita (as the ratio of effective mesh density to population density)



Note: In some countries, the socioeconomic data were not available, e.g. in Sweden and Poland.

Source: EEA/FOEN, 2011.

between 100 and 400 meshes per 1 million people. High values are found in large parts of France, in some regions in southern Finland and in some regions in Spain. Low values are observed in large parts of the United Kingdom, in Norway, in the Alps and the Po Plain (northern Italy).

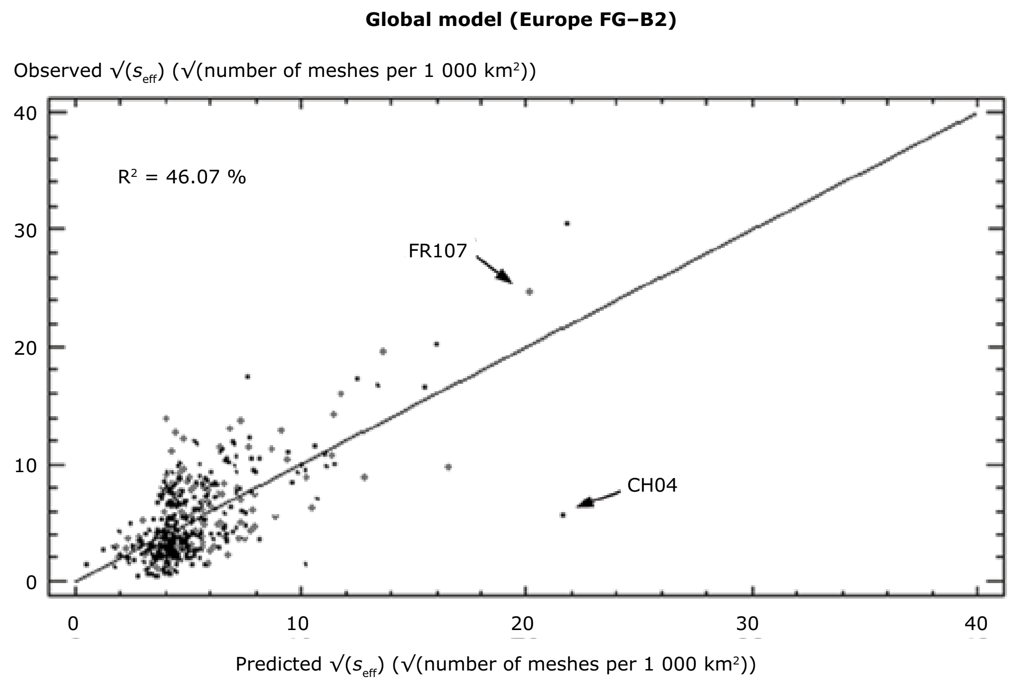
One weakness of this very rough approach is that it does not consider the situation that regions with very low population densities may still require at least a few roads for connecting the neighbouring regions located on opposite sides of the region in the centre, whereas the method of linear regression applies an intercept to capture this situation. More importantly, this approach can be applied to only one variable at a time.

The pan-European model that incorporated all the physical and socioeconomic variables exhibited a fairly strong relationship (R^2 = 46.1 %) with the effective mesh density (Figure 3.3).

The most relevant variables at the continental scale with 443 complete cases (NUTS-X regions) were population density (*PD*) and volume passenger density (*VPD*), followed by gross domestic product per capita (*GDPc*), education per capita (*EDc*), hills in % (*Hills*), high mountain areas in % (*MtSl*), environmental expenditure per capita (*EEc*), and the quantity of goods loaded and unloaded per capita (*QGLUc*), with an R^2 of 45.9 % for these eight variables alone which is fairly high. Since GDP is highly correlated with population density (regions with higher population density have a higher *GDP*), we used *GDP* per capita (*GDPc*) which varies independently of the population density of a region (and of the size of a region). We applied the same logic to the variables education per capita (*EDc*) and environmental expenditure per capita (*EEc*), and the quantity of goods loaded and unloaded per capita (*QGLUc*). This needs to be taken into account for correctly interpreting the results of the predictive models.

No other model among the competing models was more parsimonious than the one including all 10 variables (i.e. the global model). This implies that all variables are important to some degree. However,

Figure 3.3 Predicted and observed values of effective mesh density according to the pan-European predictive model



Note: The model inludes all 10 predictor variables for all NUTS-X regions in Europe, using a square root transformation for s_{eff} and *PD*. The NUTS-X regions represented by points above the diagonal line are more fragmented than predicted (e.g. FR107 Val de Marne) and those represented by points below the diagonal line are less fragmented than predicted (e.g. CH04 Zurich). (The five NUTS-X regions with s_{eff} > 1 000 meshes per 1 000 km² were excluded from the analysis: FR101 Paris, FR105 Hauts-de-Seine, FR106 Seine-Saint-Denis, UKI1 Inner London, BE10 Région de Bruxelles-Capitale.)

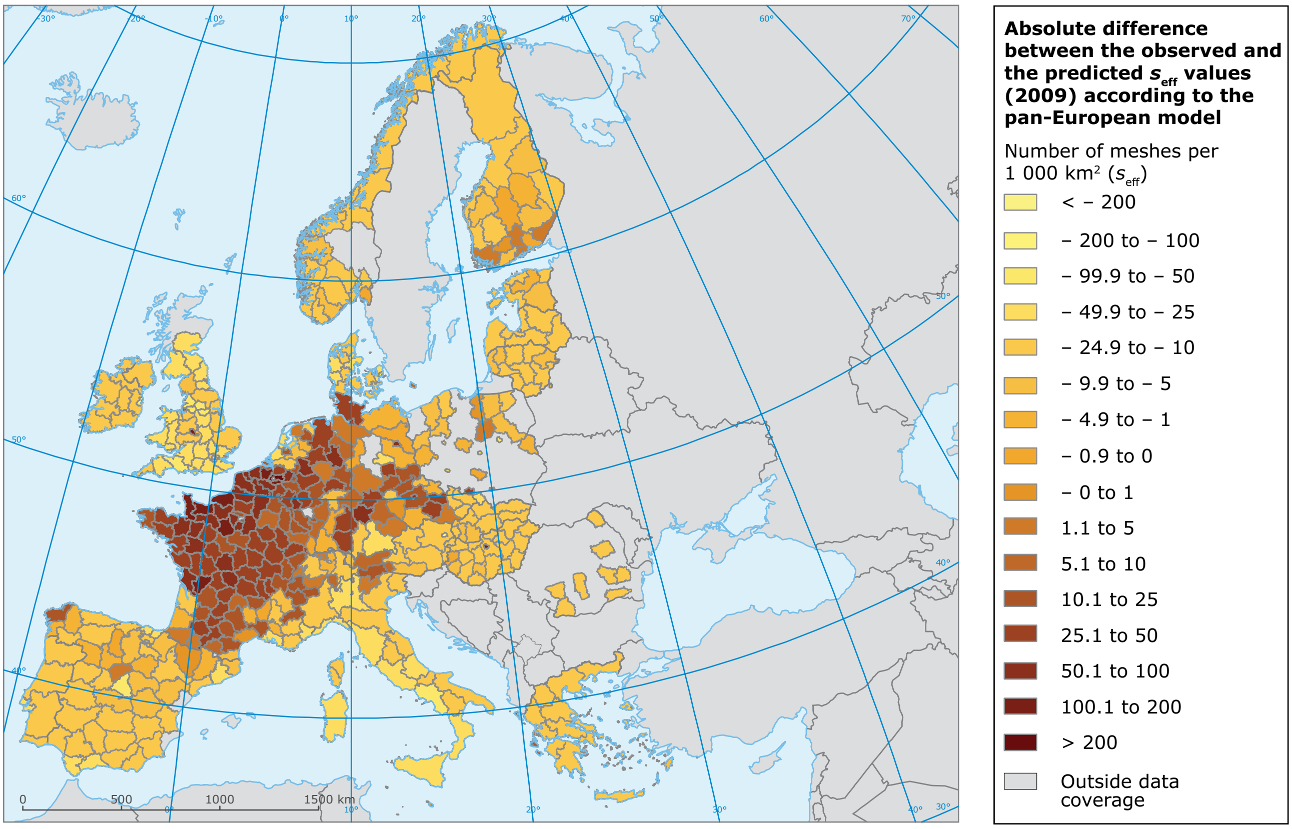
Source: EEA/FOEN, 2011.

a clear tendency was found: any model that included the variables *PD* and *GDPc* were more parsimonious than all other models that did not include either one of these two variables. Seven variables had a positive relationship with the level of fragmentation and three variables (*MtSl*, *UR* and *QGLUc*) showed a negative relationship. This was in accordance with our original hypothesis for eight variables, but opposite to our hypothesis for *QGLUc* and Island Size Index. From this result we conclude (1) that smaller islands are slightly less fragmented than large islands or NUTS-X regions on the continent, and (2) that the loading and unloading of goods per capita may either not be a good proxy for the amount of goods transported because it does not include goods on transit, or that *QGLUc* is high in places where *PD* is already high (i.e. in NUTS-X regions with larger cities) but fragmentation is not as high here as predicted by *PD* alone, i.e. higher values of *QGLUc* reducing the predicted value of fragmentation in these NUTS-X regions provide a better fit of the model. The 'second best model' besides the global model included seven variables (*VPD, GDPc, QGLUc, EEc, EDc, MtSl, Hills*).

The regression coefficients of the predictive models are given in the Landscape Fragmentation in Europe project's final report (Madriñán et al., 2011).

According to this pan-European predictive model, many regions in France and Germany are more fragmented than expected, while most of the United Kingdom and the Mediterranean, Scandinavian and large parts of the eastern European countries are less fragmented than expected. This is primarily due to the fact that different variables are most strongly related to the observed levels of fragmentation in different groups of regions, and one single model cannot capture all these differences. If those variables that are important in France and Germany were given a higher weight in the model to predict the observed levels of landscape fragmentation more accurately, then the predicted levels for the countries with lower fragmentation levels would be even higher, and the fit of the model would decrease. The resulting overall model is a compromise between all regions. The clustering of regions for which the differences between the predicted and observed values are

Map 3.8 Absolute differences between the observed and the predicted values of s_{eff} according to the pan-European model



Note: Dark brown areas are more fragmented than expected while lighter areas are less fragmented than expected. In some countries, the socioeconomic data were not available, e.g. in Sweden and Poland.

Source: EEA/FOEN, 2011.

positive (or negative, respectively) indicates that the relationship with the predictor variables differs in different sets of countries. Therefore, different predictive models would be more appropriate to reveal these different relationships and the relevant variables.

3.2.2 *A set of six models explaining landscape fragmentation at the regional scale*

When the global pan-European model was observed more closely, we found several clusters of regions that can be distinguished from each other. Based on the observation that the highest fragmentation values belonged to western Europe, we performed an analysis for each of the countries of western Europe. For Germany and the Benelux countries, the new models resulted in an R^2 higher than 80 %. France did not follow this trend, the R^2 was just 50 %. The northern part of the country behaved in a similar way as the other western countries, but the s_{eff} values in the southern part were more similar to values found in the Mediterranean regions. With these results in mind, we studied the cloud of residuals from the pan-European model and identified six main clusters (Map 3.9):

1. Group A: Belgium, Denmark, Germany, northern France, Luxembourg, the Netherlands (countries with access to the sea, but excluding the southern part of France that is more similar to the Mediterranean countries);

2. Group B: Austria, the Czech Republic, and Switzerland (countries close to the Alps and with 'continental' characteristics);

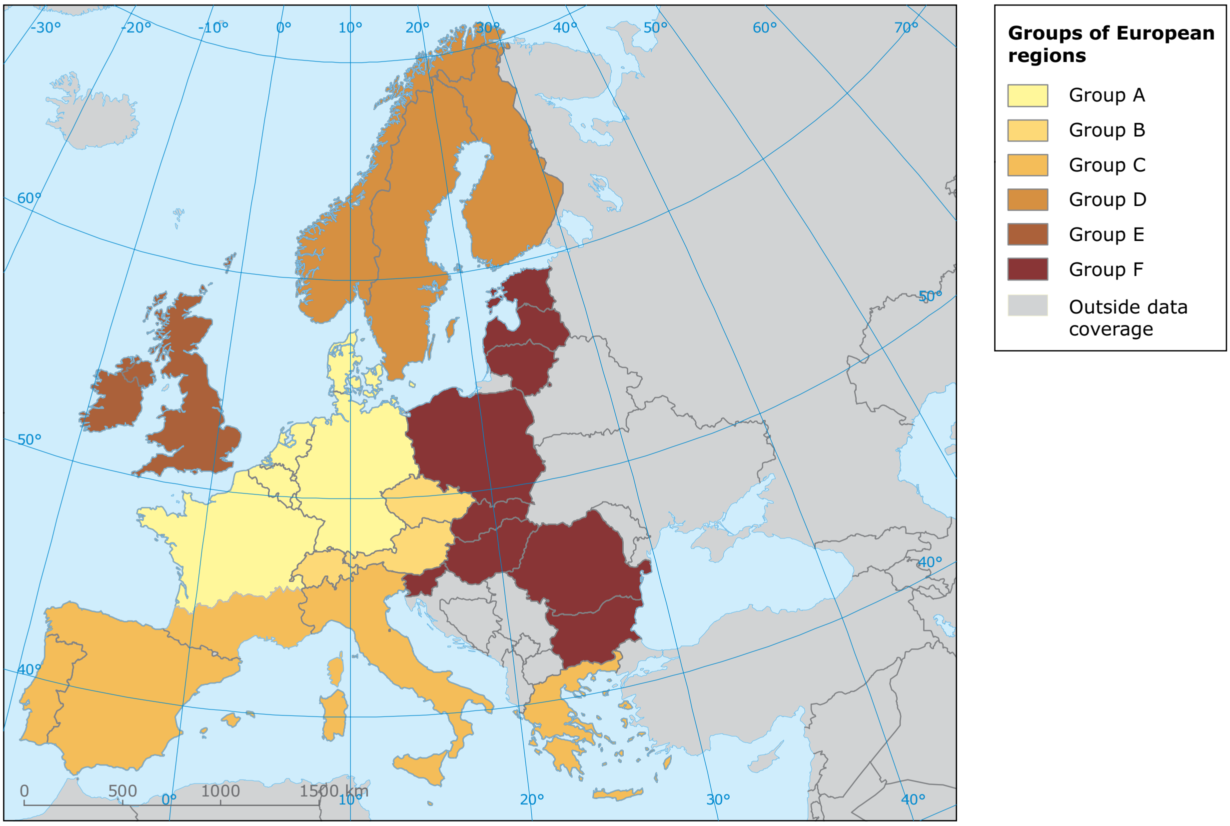
3. Group C: southern France, Greece, Italy, Malta, Portugal, Spain (all Mediterranean countries, including the southern part of France as it shows patterns that are more similar to this group of regions than to Group A);

4. Group D: Finland, Norway, Sweden (Scandinavian countries);

5. Group E: Ireland and the United Kingdom;

6. Group F: Bulgaria, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, and Slovenia.

Map 3.9 Six groups of regions identified and used for separate analysis



Source: EEA/FOEN, 2011.

These six clusters match well with the classification of the four European regions recognised by the UN (United Nations, 2010): western Europe comprises Groups A and B, southern Europe = Group C, northern Europe comprises Groups D and E, eastern Europe = Group F.

The six models provided a much better fit than the pan-European model from Section 3.2.1 (Figure 3.4, Table 3.1). The regions of **Group A** cover the most densely populated part of Europe and also the most fragmented (R^2 = 75.8 %). Accordingly, population density has an important role in explaining landscape fragmentation in this part of Europe: population density appears to be the main driver of landscape fragmentation in this group. The second most important variable is *GDP* per capita. In this group of regions, eight independent variables behaved as expected in our original hypothesis. However, the relationship of *EEc* with s_{eff} was negative, indicating that regions that have a higher investment in *EEc* are less fragmented than regions with lower environmental investments, all else being equal. The negative relationship with *GDP* per capita indicates that *GDPc* is higher in NUTS-X regions with high population densities (e.g. larger cities) where the level of fragmentation is relatively lower because people live closer together, and in rural regions with low *PD* and low *GDPc*, the level of fragmentation is relatively higher because the settlement patterns are more spread out.

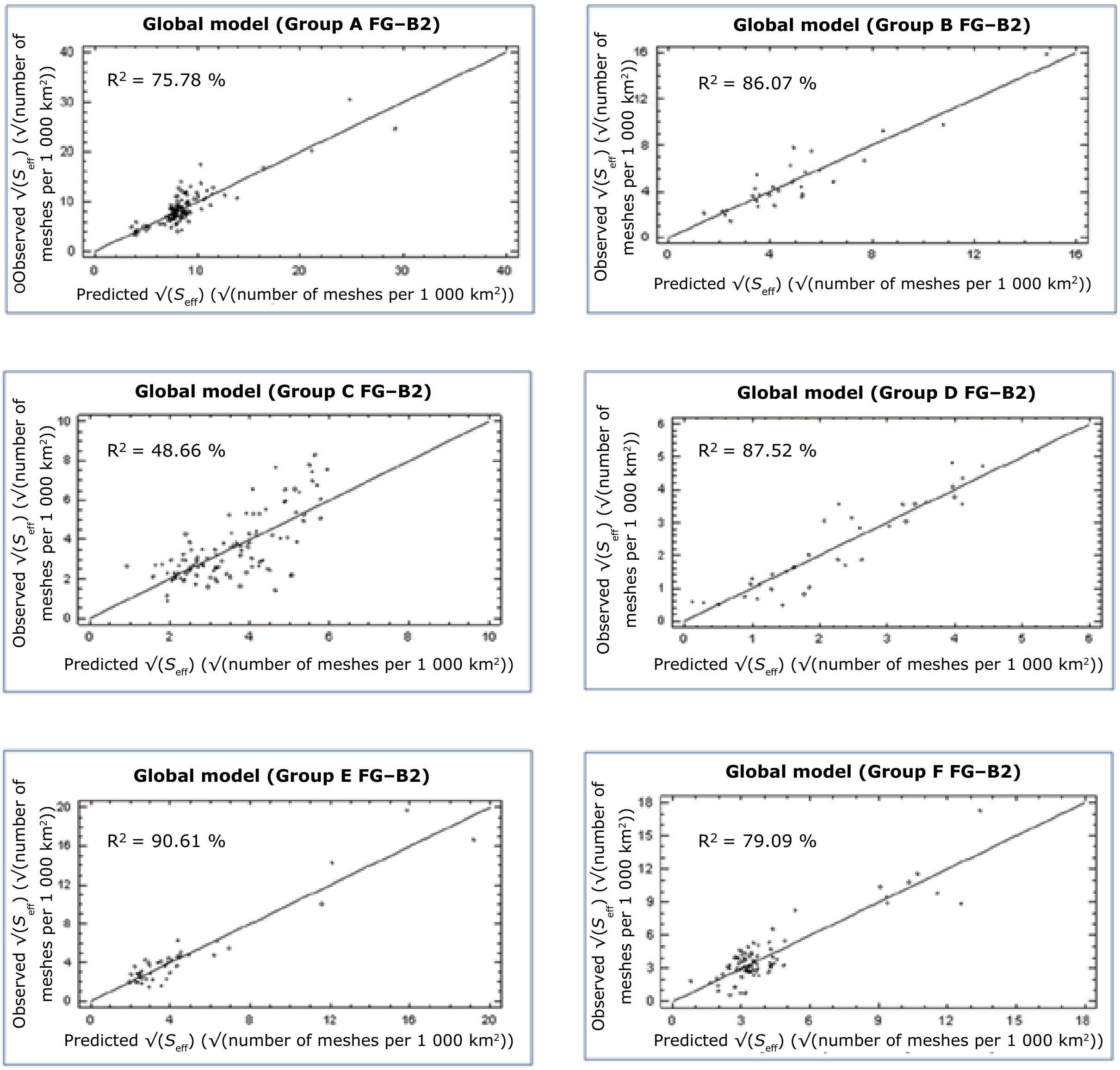
In **Group B** (R^2 = 86.1 %), most of the variation in s_{eff} values was explained by population density and volume of passenger density. This group includes very heterogeneous fragmentation values, and regions with relatively high and low fragmentation levels are often adjacent to each other. In this group of regions seven independent variables behaved as expected in our original hypothesis. The variable *Hills* behaved in a similar way as in the Mediterranean countries of Group C (positive relationship), as expected for Austria and Switzerland, but it contributed little explanatory power to the predictive model. In the global model including all nine variables, *GDP* per capita and volume of passenger density had negative coefficients, indicating that population density already predicted high levels of fragmentation when *GDPc* or *VPD* were high, i.e. in densely populated NUTS-X regions. In rural regions where population density is low, fragmentation levels are often higher than predicted by population density alone, and *GDPc* or *VPD* are also low. Therefore, negative relationships of *GDPc* and *VPD* increased the fit of the model. (Island size Index was not included since there are no islands in Group B).

In **Group C**, the highest R^2 (48.66 %) resulted for the model that included all 10 variables. This was the lowest R^2 among all six groups, indicating that other drivers of fragmentation are also relevant in this group which are not covered by the 10 variables. The best model included the five variables *EDc* + *Hills* + *UR* + *GDPc* + *VPD* (Table 3.1). For the Mediterranean countries, regions with higher proportion of hills are usually more fragmented. In group C, all independent variables behaved as expected in our original hypothesis, except for *GDP* per capita. In the global model, *GDPc* had a negative regression coefficient as in Groups A and B (see above).

The Scandinavian countries in **Group D** differ in an interesting way from other parts of Europe (R^2 = 87.5 %). The fragmentation values in these regions are low, while *GDPc* values are generally high, compared to other parts of Europe. The fact that population densities are low in most regions resulted in a low influence of population density in the top model, which is dominated by the variables *EEc*, *GDPc* and *UR*. In the global model that included all variables, four relationships went in the expected direction, but the other four variables were opposite to our initial hypothesis. For example, the two transport variables (*VPD* and *QGLUc*) exhibited a negative relationship in the global model (but positive when run independently). This may be in part due to the fact that much of the freight transport in these countries is conducted via ocean vessels that do not directly contribute to landscape fragmentation. Another reason may be the limited amount of motorways in these countries (Norway's Ministry of Transportation, 2010). The other two variables are *EEc* and *IsI*, i.e. regions with higher environmental expenditure and smaller island size are less fragmented, all else being equal. The variable *PD* that is very important in the other groups only explained 0.1 % of the variation in s_{eff} values, and in several models its coefficient had a negative sign (but not in the global model). These findings suggested that *PD* was not related to the level of landscape fragmentation in this part of Europe. In order of importance, the variables that explained most of the variation in fragmentation values for this group were *EEc* with an R^2 of 44.2 %, *UR* with an R^2 of 11 % and *GDPc* with an R^2 of 5.6 %.

Group E (R^2 = 90.6 %) covering the United Kingdom and Ireland provides an example of the development of fragmentation patterns progressing from urban centres. In these regions, the high fragmentation values occur mostly around the major urban centres with high population densities,

Figure 3.4 Predicted and observed values of effective mesh density according to the six predictive models for the six groups of regions studied in Europe



Note: All models shown include all available variables in each group and use a square root transformation for s_{eff}.

Source: EEA/FOEN, 2011.

and accordingly, they exhibit a strong relationship: population density alone explained 82.5 % of the variation in s_{eff} values. Other variables were also important when they were included in the model, but less important than population density.

In **Group F** (R^2 = 79.1%), the joint contribution of the two independent variables *PD* and *VPD* explained most of the variation in s_{eff} values (47.3 %). The joint contributions of *GDPc* with *PD* (7.7 %) and *VPD* (14.5 %) were also important. For the regions with complete information (n = 82), our global model performed well, accounting for 79 % of the variation in s_{eff} values. In this group, six variables in the global model behaved as expected in our original hypothesis, but four variables did not: *QGLUc*, *EEc*, *Hills* and *IsI*, for similar reasons as discussed above. There was only one island in this group (in the Baltic Sea) with comparatively lower levels of fragmentation than the continental areas.

Table 3.1 Most parsimonious model in each group, starting with the pan-European model, followed by the best models for the six groups

Part of Europe covered	Variables included in most parsimonious model	R^2 of most parsimonious model (%)	R^2 of global model (%)	Variation explained (R^2) by most important variables of best three-variable model (%)
Pan-European model	*PD + VPD + GDPc + QGLUc + EDc + EEc + UR + MtSl + IsI + Hills*	46.07	46.07	*PD ∩ VPD*: 36.74 *GDPc*: 1.58 *PD ∩ VPD ∩ GDPc: 6.45*
Western Europe — Group A	*PD + GDPc + QGLUc + EEc + EDc + UR*	83.54	84.05	*PD*: 77.14 *GDPc*: 1.88 *QGLUc*: 0.23 *PD ∩ QGLUc: 1.72*
Western Europe — Group B	*PD + VPD + QGLUc + EEc + UR*	73.69	86.07	*PD*: 50.47 *VPD*: 41.87 *PD ∩ VPD*: – 29.17 *UR*: 4.9
Southern Europe — Group C	*EDc +Hills + UR + GDPc + VPD*	37.79	48.66	EDc: 19.57 *Hills*: 12.41 *UR*: 7.04
Northern Europe — Group D	*EEc + GDPc + UR + PD + VPD*	76.17	87.52	*EEc*: 45.63 *GDPc*: 19.79 *UR: 16.31* *GDPc ∩ EEc*: – 11.67 *EEc ∩ UR: – 15.56*
Northern Europe — Group E	*PD + VPD + EDc*	85.17	90.61	*PD*: 2.12 *VPD*: 2.59 *PD ∩ VPD*: 77.88 *EDc*: 0.96
Eastern Europe — Group F	*PD + VPD + GDPc*	71.11	79.09	*PD*: 3.77 *VPD*: 2.09 *PD ∩ VPD*: 47.35 *GDPc*: 0.53 *VPD ∩ GDPc: 14.47*

Note: Column 3 gives the variation explained by the simplest model, and column 4 gives the variation explained by all variables in each group (i.e. global model). The last column gives the variation explained by the best three-variable model, based on variance partitioning. Unique and joint contributions are given, where ∩ indicates the joint contributions (selection; for more information see full report by Madriñán et al., 2011).

Abbreviations: *PD* = population density, *GDPc* = gross domestic product per capita, *VPD* = volume passenger density, *QGLUc* = quantity of goods loaded and unloaded per capita, *EEc* = environmental expenditure of the public sector per capita, *EDc* = education expenditure per capita, *UR* = unemployment rate, *MtSl* = percentage of high mountains with steep slopes in the region, *Hills* = percentage of hilly terrain in the region, and *IsI* = island size index.

Source: EEA/FOEN, 2011.

Other groupings of the NUTS-X regions would be of interest in future studies as well. For example, a group of mountainous areas (covering parts of Italy, Slovenia, France, Switzerland, Austria, among others), groups according to biogeographical zones of Europe, or the urban-rural typology of NUTS-3 regions (European Commission, 2007).

3.3 Which regions are more or less fragmented than expected?

The grouping of the 28 countries investigated into six groups proved to be successful. Five of the six predictive models for the six groups had much higher R^2 than for the overall European model

(Table 3.1). As a consequence, the ensemble model that is created by assembling the best models of each of the six groups of regions for Europe should be used for predicting levels of landscape fragmentation in Europe (Figure 3.4). In the four groups A, B, E and F, population density appears to be the main driver of landscape fragmentation, but not in groups C and D, indicating that other variables are more important in the Mediterranean and Scandinavian countries.

For **Group A**, our model predicted the fragmentation values of most of the regions well (most differences ranged between – 10 % to + 10 %). The northern coast of France is more fragmented than expected while the south-eastern and eastern parts of Germany are slightly less fragmented than expected. The regions with the most extreme differences were FR252 (Manche), FR242 (Eure-et-Loir), and BE24 (Prov. Vlaams-Brabant) which are at least twice as fragmented than expected, while the regions FR612 (Gironde), DE21 (Oberbayern) und NL23 (Flevoland) are more than 50 % less fragmented than predicted by our model. Almost all NUTS-X regions in Belgium are more (by up to 200 %) fragmented than predicted. In general, the fragmentation values that are higher than predicted follow a clear pattern along the north coast of France, along the motorways connecting the ports of Calais and Dunkirk, and covering north-central Germany. Fragmentation values that are lower than expected are located primarily close to the borders with group B. An interesting case is the Netherlands. Even though it has one of the highest population density values in Europe, 9 out of its 12 NUTS-X regions are less fragmented than expected, in contrast to its neighbour Belgium which has a different governance and regional planning history. We conclude that a region is more fragmented than other regions if it has high population density, high volumes of goods transported, low unemployment rate, and high expenditure for education per capita. To capture differences in land-use planning (e.g. between Belgium and the Netherlands), additional variables such as existence of regional planning, the degree of which its application is compulsory, and the time since its implementation would need to be included in the analysis in future studies.

Our predictive models for **Group B** showed that Switzerland is a very diverse country with higher than expected values in some regions followed by lower than expected values in neighbouring regions. In general our model captured well the observed values of fragmentation in Austria. Examples of regions that are much more fragmented than expected include CH03 (Nordwestschweiz), AT12 (Niederösterreich), and CZ042 (Ustecky kraj). In this group of regions, the geophysical variables had higher explanatory power than in any other region (> 12 % of the total variation), highlighting the importance of the Alps in shaping fragmentation patterns.

Regarding our initial hypothesis, we conclude that for this group, a region is more fragmented than other regions if it has a high population density, a high education expenditure per capita, high volumes of goods transported, and a low unemployment rate.

In **Group C**, the metropolitan areas have retained a strong monocentric pattern of employment, but there is not a single city that concentrates most of the population of each country. The lack of employment opportunities in rural regions leads to a concentration of the most educated part of the population in urban centres.

In general, the regions in the south-west of France are more fragmented than expected. In Spain, the regions of La Coruña (ES111), Valladolid (ES418) and Palencia (ES414) are significantly more fragmented than expected, while Madrid (ES300) and Badajoz (ES431) are as fragmented as expected. In Portugal, the region of Lisboa (PT17) is clearly more fragmented than expected, whereas the other regions in Portugal are as fragmented as expected or slightly less. In group C, a region is more likely to be fragmented than other regions if it has a high proportion of hills, a high expenditure for education, and a low unemployment rate. However, there is a need to explore additional variables to be able to better explain the fragmentation patterns observed in these regions.

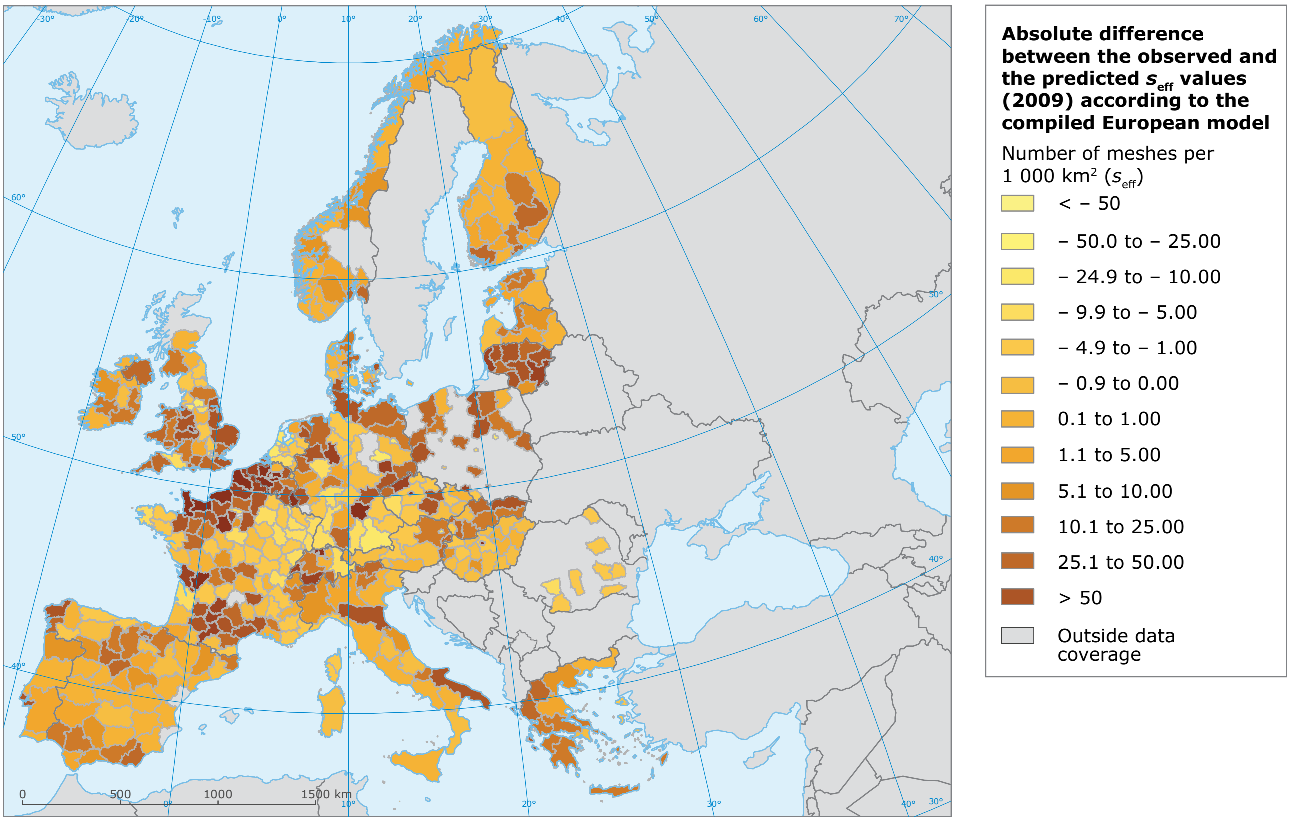
In **Group D**, most NUTS-X regions are sparsely populated, and the population is concentrated around the big urban centres like Oslo and Helsinki. The regions in this group are among the least fragmented ones in Europe in all three fragmentation geometries. In fact, even the most fragmented NUTS-X regions in Norway and Finland have relatively low levels of fragmentation. The fragmentation levels are well predicted by our models. A region in this group is more fragmented than other regions if it has higher population density, higher per capita income, and a lower unemployment rate.

For **Group E**, our results showed that urban areas are clearly more fragmented than expected, while most of the other regions are well predicted by our model. An example of this trend is given by the region UKG3 (West Midlands) which is a metropolitan county including three different urban centres (Birmingham, Coventry and Wolverhampton), with a difference of 118 meshes per 1 000 km². Five regions are significantly less fragmented than predicted, and the differences range between 37 and 73 meshes per 1 000 km² (UKD3 Greater Manchester, UKE3 South Yorkshire, UKE4 West Yorkshire, UKI2 Outer London, UKK2 Dorset and Somerset). For all other regions, the absolute difference is less than 25 meshes per 1 000 km². It is a common trend in this group of regions that the fragmentation values of neighbouring regions tend to be similar to each other. As a rule of thumb, we conclude that England is more fragmented than expected; Scotland is less fragmented than expected, while regions in Wales and Ireland are as fragmented as expected. A region is likely to be more fragmented than other regions if it has a higher per capita income, a higher expenditure in education and larger volumes of freight and passenger transport.

In **Group F**, a significant amount of socioeconomic information was missing for many regions. For the regions with complete information ($n = 82$), our global model performed well, accounting for over 79 % of the variation in s_{eff} values. According to our predictions, the regions that are much more fragmented than predicted are PL227 (Rybnicko-jastrzebski) and HU101 (Budapest) with a difference of 38 and 51 meshes per 1 000 km². In general, most regions in this group were slightly less fragmented than expected with the exception of the regions than contain large urban areas that were often somehow more fragmented than expected. For this group, we conclude that a region is likely to be more fragmented than other regions if it has higher population density, higher volume of passengers transported, higher per capita income, and a lower unemployment rate.

The ensemble model created by assembling the best model of the six groups of regions, predicted fragmentation levels in most regions in Europe well

Map 3.10 Absolute differences between the observed and the predicted values of s_{eff} using the six global models for groups A to F



Note: Dark brown areas are more fragmented than expected while light yellow areas are less fragmented than expected. In some countries, the socioeconomic data were not available, e.g. in Sweden and Poland.

Source: EEA/FOEN, 2011.

(often within + 10 and – 10 meshes per 1 000 km²). Many predicted values for the regions belonging to western and central Europe are almost identical to the observed values for s_{eff}, while the regions of eastern Europe are often a bit less fragmented than expected. The regions in Scandinavia, the United Kingdom and Ireland are very often a bit more fragmented than expected. In the Mediterranean regions, the predicted values are often close to the observed values, but we also find several regions that are much more or much less fragmented than expected. Overall, this compiled model is a much better tool for predicting landscape fragmentation at the continental scale than the pan-European model (Figure 3.3). For each part in Europe, different driving forces are responsible for the current levels of landscape fragmentation, which is reflected in the large differences between the predictive models that ranked best. This information can be used to identify regions that have performed better than others in terms of avoiding landscape fragmentation while serving the land-use needs of their population and their economic development, as reflected in the seven socioeconomic variables included in the analysis.

In the first three groups (western Europe and the Mediterranean countries), we found that *GDPc* is often high in regions where *PD* is already high, but fragmentation is not as high as predicted by *PD* alone (even when we used the square root of *PD* in the model). The population here is often concentrated, and higher *GDPc* and *VPD* do not necessarily contribute to higher levels of fragmentation. In this situation, higher values of *GDPc* reduce the predicted value of fragmentation in the NUTS-X regions to provide a better fit of the models, i.e. *GDPc* shows a negative relationship with landscape fragmentation in models that include *PD*. This was not the case in Scandinavia, the United Kingdom and Ireland, and the eastern countries, where higher *GDPc* contributed to higher levels of fragmentation.

To answer the question why certain regions are more (or less) fragmented than predicted by the statistical model, more detailed research about the history and the political and economic conditions of different parts of Europe would be required which are not captured by the 10 predictive variables. As an example, the laws about regional planning are not well adopted and put into action in north-western Switzerland, contributing to the higher levels in landscape fragmentation than in other parts of Switzerland. Another example involves the large tax differences among the cantons in Switzerland. To capture such differences between cantons and address questions regarding policy implementation at this scale, an analysis on a smaller scale would be required, whereas the NUTS-X regions in Switzerland are a combination of several cantons.

Some relationships between the level of fragmentation and the 10 independent variables indicate that these variables are driving forces of landscape fragmentation, but this may not always be true. For example, large transport volumes of passengers (*VPD*) and goods (*QGLUc*) may not only **cause** higher levels of fragmentation (reflecting a high demand for transportation infrastructure), but may also be **a response** to the availability of roads and railways to some degree. Thus, there are **feedback loops**, which can be studied using a systems-theoretic approach. In addition, roads are often built to stimulate economic development and increase *GDPc* rather than as a response to economic growth (e.g. in Schleswig-Holstein DEF0 which is the most northern state of Germany). These questions would be interesting subjects for future studies.

4 Policy relevance and implications

4.1 The need for monitoring the degree of landscape fragmentation

The aims of environmental monitoring are to discover and better understand changes in the environment. The results presented in this report are relevant for biodiversity, including wildlife populations, ecological communities, ecosystems and ecosystem services. In addition, they portray the character and appearance of the landscape and its recreational value. Therefore, the results are applicable in several types of monitoring: biodiversity monitoring, environmental monitoring, sustainability monitoring, and landscape quality monitoring. Accordingly, the findings of this study should be adopted in the European monitoring systems, and in the land accounting and ecosystem accounting efforts of the European Environment Agency (EEA, 2006b; Romanowicz et al., 2007; Weber, 2007).

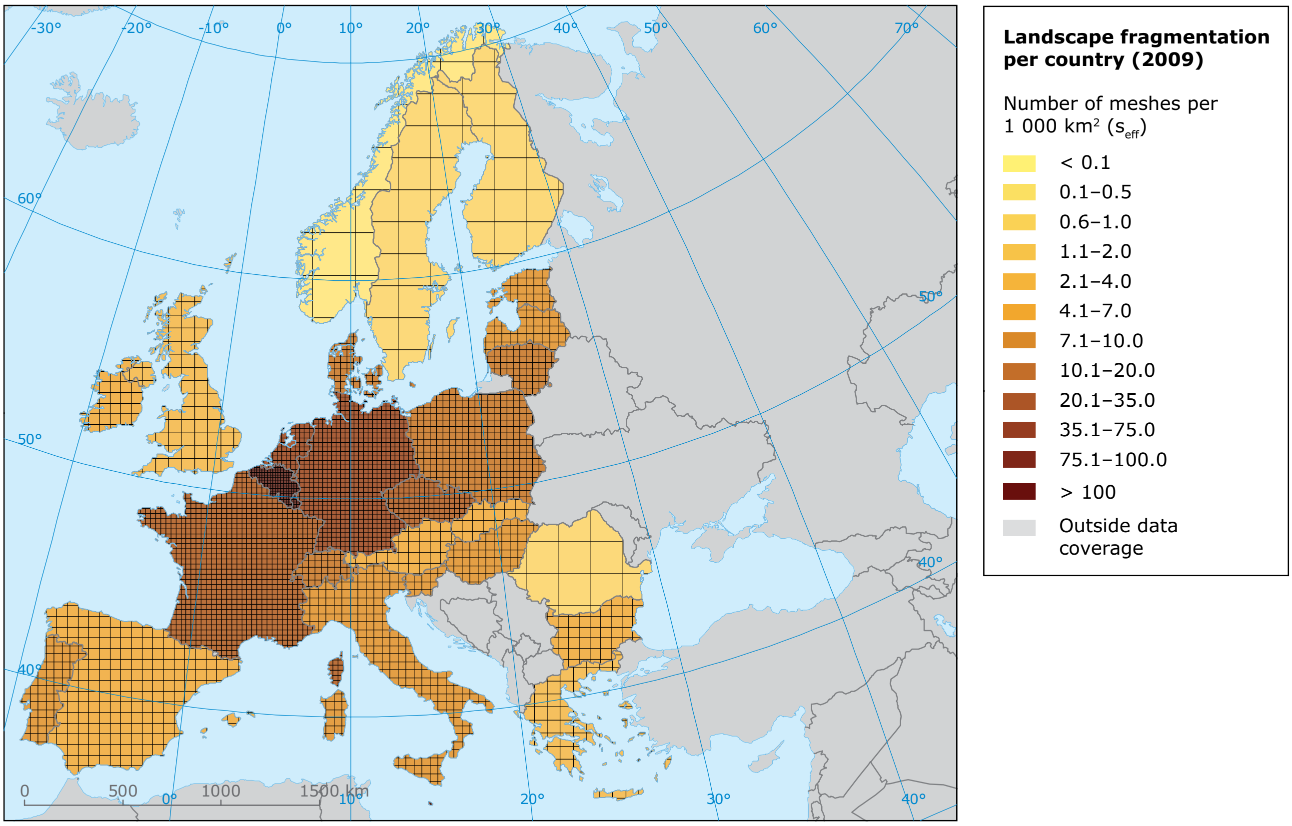
The results have already been included as a pressure indicator in the *2009 Environment Policy Review* of the European Commission (European Commission, 2010b) and in the *European environment —state and outlook 2010* report (SOER 2010) (EEA, 2010a). Ideally, the update would be done every three to five years, but this will depend on data availability. Potential driving forces that are not yet monitored should also be observed and included in future statistical analysis. The predictive models for the degree of fragmentation are no substitute for monitoring fragmentation trends directly. Rather, the predictive models should be used to determine if the actual fragmentation levels increase faster or more slowly than the models would predict, and at what point economic development is successfully decoupled from further degradation of the environment.

The issues related to data inconsistency in the TeleAtlas dataset between the years 2002 and 2009 highlight the need for a rigorous and consistent definition of the fragmentation geometries in space and time to provide reliable monitoring data on the European level. This implies that future monitoring should be based on exactly the same fragmentation geometries and fragmenting elements as listed in Chapter 2. The use of the same fragmentation geometries is a necessary precondition for being able to compare the results between countries. Supplementary fragmentation geometries can be added as well.

The fragmentation geometries presented in this report are considered appropriate for most countries in Europe, most importantly fragmentation geometry B2 'Fragmentation of Non-Mountainous Land Areas'. Therefore, the results of this study should also be included in the national monitoring systems of the 28 countries investigated, unless better data about the level of fragmentation that contain earlier points in time are already available, as in Switzerland (Figure 4.1a). More detailed fragmentation geometries may be more appropriate in some countries when they are better adapted to the particular conditions in a country and data are available at higher resolution (e.g. for including built-up areas more accurately). Therefore, countries should not be forced to use the same fragmentation geometries. For transportation planning and policy implementation at the country level, further analysis at smaller scales is necessary.

The effective mesh size and effective mesh density method has already been implemented in various monitoring systems. For example, the Swiss Federal Statistical Office (SFSO), the Swiss Federal Office for the Environment (FOEN), and the Swiss Federal Office for Spatial Development (ARE) launched the *Monitoring Sustainable Development project* (MONET) in 2000 to establish a system of indicators for sustainable development in Switzerland. MONET is representative of many other monitoring systems of sustainable development. It uses 163 indicators that encompass social, economic and environmental issues (SFSO/SAEFL/ARE 2004). The effective mesh size has recently been included in MONET (Figure 4.1a; Jaeger et al., 2008; BFS, 2009). MONET applies 17 criteria for indicator selection, related to frame of reference (7 criteria), user friendliness (4 criteria), validity (2 criteria), and data availability (4 criteria). The assessment of m_{eff} according to these criteria reveals a high suitability as it meets

Map 4.1 Illustration of the level of landscape fragmentation measured by effective mesh size and represented as regular grid



Note: The value of the effective mesh size per country is represented as a regular grid (a proxy cell size of m_{eff} in km²).

Source: EEA/FOEN, 2011.

all 17 criteria well (Jaeger et al., 2008). The effective mesh size is also applied as a pressure indicator in the *Swiss Biodiversity Monitoring System* (http://www.biodiversitymonitoring.ch/) and in the novel *Swiss Landscape Monitoring* system (LABES; Roth et al., 2010; Schwick and Spichtig in prep.). A striking feature of the landscape fragmentation study from Switzerland is that the time series go back to 1885, covering more than 120 years (Bertiller et al. 2007). The indicator is updated every six years. Two fragmentation geometries are used in these monitoring programmes in Switzerland (Figure 4.1a):

1. CH-1: the land areas below 2 100 meters considering urban areas, railway lines, and roads **up to class 2** (according to the VECTOR25 dataset); and

2. CH-2: the land areas below 2 100 meters considering urban areas, railway lines, and roads **up to class 4** (according to the VECTOR25 dataset).

Fragmentation geometry CH-1 has the objective to track the fragmentation of landscapes by major roads as a threat to biodiversity and to indicate the decline of silent (noise-free) areas. In addition, fragmentation geometry CH-2 observes the additional contribution to fragmentation by minor roads and documents the spatial extent of this phenomenon. The results show that the increase in fragmentation in Switzerland caused by major roads (CH-1) is clearly less steep today than it was 30 years ago. This is primarily due to the fact that the large unfragmented areas in the Alps are now protected by the Swiss constitution from further fragmentation. However, landscape fragmentation by minor roads (CH-2) is still increasing at an alarming rate (Figure 4.1a). Another instructive example is given by the Environmental Report from Baden-Württemberg, Germany, where m_{eff} was implemented in 2003 (Figure 4.1b; State Institute for Environment, Measurements and Nature Conservation Baden-Württemberg 2006).

Figure 4.1 Examples of the use of effective mesh density in monitoring systems of sustainable development, biodiversity, and landscape quality

Note: (a) Switzerland: the data are used in the Swiss Landscape Monitoring System (LABES), in the Biodiversity Monitoring Switzerland, and in the Swiss Monitoring System of Sustainable Development (MONET). Two fragmentation geometries are shown: 'CH-1: Degree of Fragmentation class 2' (shown in blue) includes land areas below 2 100 m with roads up to class 2, and 'CH-2: Degree of Fragmentation class 4' (shown in red) with roads up to class 4 for 1960–2008.

Note that 'Degree of Fragmentation class 2' also includes values for 1885 and 1935 which are based on a different dataset.

(b) Baden-Württemberg: times series since 1930 for two fragmentation geometries: with and without municipal roads. The values in Switzerland are for the entire country, including the Jura mountains and parts of the Alps up to 2 100 m. Therefore, they are much lower than the values in Baden-Württemberg. However, the level of fragmentation in the Swiss Lowlands is much higher than the average and similar to the values in Baden-Württemberg (see Roth et al. 2010).

Source: Roth et al., 2010; Bertiller et al., 2007; Esswein and Schwarz-von Raumer, 2008.

In Germany, effective mesh size is applied as one of 24 core indicators for environmental monitoring (Schupp, 2005). It is also used in the *German National Strategy on Biological Diversity* (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety ,2007; EEA, 2010b). The German Federal Environmental Agency (UBA) has already adopted m_{eff} to propose limits to curtail landscape fragmentation in Germany (UBA, 2003; Penn-Bressel, 2005).

In the context of indicator systems for biodiversity, an indicator of landscape fragmentation serves as a proxy of the pressure on biodiversity (according to the DPSIR model = drivers-pressure-state-impact-response model, adopted by the EEA). One indicator related to the fragmentation of forests has already been included in the SOER 2010 framework (indicator SEBI 013, http://www.eea.europa.eu/data-and-maps/indicators/fragmentation-of-natural-and-semi/fragmentation-of-natural-and-semi; Estreguil and Mouton, 2009).

Indicators of landscape fragmentation are also relevant for monitoring transport and environment integration. To measure progress towards existing objectives and targets on the European level, EEA developed the TERM (Transport and Environment Reporting Mechanism) and has published TERM reports since 2000 (EEA, 2010c). Including landscape fragmentation indicators in TERM would contribute to a better understanding of spatial effects of transportation infrastructure.

Landscape fragmentation is also a threat to landscape quality and to the sustainability of human land-use, e.g. long-term supply of a series of ecosystem services to humans. Landscape fragmentation changes the visual perception of landscapes: roads, railways, and built-up areas are the most prominent contributors to the transformation of natural landscapes into technically dominated cultural landscapes and subdivide landscapes into fragments. As a result, the landscape is not perceived as an entity any more. In contrast to the impacts of landscape fragmentation on biodiversity, many other fragmenting elements also have an influence on the recreational quality of landscapes such as power lines, ski lifts, and pressure lines, and can be included in additional fragmentation geometries.

Landscapes with high recreational quality are centres of tourism in Europe. Prime examples are the Alps and the coasts of the Mediterranean countries. While in the Alps, fragmentation is concentrated in the valleys and the higher elevations exhibit relatively low levels of fragmentation, the degree of fragmentation along the coasts of the Mediterranean countries is high (see maps in Chapter 3). It is expected that recreation activities in Europe will grow annually with rates of about 5 % over the next years (European Travel Commission, 2010). This will lead to further growth of the built-up areas and new transport infrastructure, and will result in higher landscape fragmentation in many recreational areas. These landscapes are in high danger of being more and more fragmented and of losing much of their remaining recreational quality and beauty. Thus, there is an urgent need for action.

An example of a monitoring system of landscape quality is the ongoing project *Landscape Quality* in the *Landscape Monitoring in Switzerland program* (LABES) by the Swiss FOEN. Through interviews with experts, a set of factors that influence landscape quality was determined. In addition, 3 000 interviews with respondents in three different regions of Switzerland were conducted to capture their subjective perceptions. Noise, pollution and landscape fragmentation were unanimously identified as negative impacts of transportation infrastructure on landscape quality. Accordingly, landscapes with higher degrees of fragmentation have a lower landscape quality and they lose parts of their function as recreational areas.

The reassuring experiences and results about the monitoring of landscape quality in Switzerland should be applied for implementing a monitoring system of landscape quality at the European level as well in the near future. Landscape fragmentation in particular is an indicator of high importance for monitoring landscape quality, and the results from this report can be directly included for this purpose at the European scale. In addition to the degree of landscape fragmentation, other indicators of landscape quality should also be considered in the future.

4.2 Implications for nature conservation, traffic and urban planning

4.2.1 Application as a tool for performance review

Measures for controlling landscape fragmentation can only be implemented effectively if there is an awareness of the problem and feasible solutions are proposed. Decision-makers and the general public should therefore be made more aware of the problems of landscape fragmentation and habitat loss and need to be informed about suitable measures. The setting of limits can play an important role for this objective. Once quantitative targets or limits for the future degree of landscape fragmentation will be available, the degree of fragmentation can be recalculated after new roads have been built or existing roads have been removed, and compared to the target or limit (Box 4.1). This is already possible in the planning stages of the construction or removal of transportation infrastructure. Maps of planned transportation infrastructure can be combined with models for predicting future land-use changes, and the resulting degree of fragmentation can be compared to the target. Thus, the use of quantitative data about fragmentation as a tool for performance review is an influential approach for increasing awareness and guiding efforts for minimising landscape fragmentation. Such analysis for the purpose of performance review is applicable with regard to both biodiversity and landscape quality. The results of this report are highly relevant for environmental monitoring and provide a comparative basis for further investigations. We recommend that the fragmentation values be updated on a regular basis to detect trends in the development of landscape fragmentation in Europe.

The effective mesh density is an important criterion for consideration in transportation planning and regional planning. However, it is clearly not the only relevant indicator and cannot replace other important indicators. At least as important are habitat amount and habitat quality for all relevant species in the study area, for both current and potential habitats. If this is ignored, there is a danger that road construction may be considered unproblematic by decision-makers if the new roads are combined with the construction of wildlife passages and fences. This is deceptive when habitat amount and quality in these landscapes continue to decline (Fahrig, 2001, 2002). Therefore, the conservation and restoration of wildlife habitats must be the first priority. Wildlife passages will be useless if there is not enough habitat left to connect. For example, road density in Canton

Box 4.1 Applying the method

The method of effective mesh density and effective mesh size can be used at any level (e.g. NUTS-X regions, districts, or at the local scale) as an instrument of analysis for these purposes:

1. Data on planned future development reveal the extent to which planned transport routes will increase fragmentation and can be compared to the targets and to previous trends. This approach will take into account the cumulative effects of several projects combined (and the predicted expansion of urban areas) on the effective mesh density.

2. Various planning alternatives for transport infrastructure and built-up areas can be assessed and compared with respect to their impacts on the effective mesh density. Consideration should be given to the cumulative effects of all planned future developments and their interactions. The method can be broadened to encompass the issue of landscape quality. Among the possibilities here are: the inclusion of weights for landscape character, recreational quality, or the ecological quality of affected habitats; the inclusion of noise bands; and the inclusion of wildlife passages and probabilities of crossing success of transport routes.

3. The extent to which each category of transport route contributes to the total degree of fragmentation can be determined. Such values can, for example, indicate threat levels for the remaining ecological networks, since smaller transport routes may serve as an indication where expansion might be envisaged by planners in the future if traffic levels rise.

4. Using this method, specific suggestions can be put forward for the removal of transport routes, which would have a particularly positive effect on effective mesh density.

5. It would be informative to study the extent to which regions are successful in decoupling their economic welfare from their level of landscape fragmentation, i.e. where economic development is accompanied by increase in landscape fragmentation and where it occurs without additional fragmentation.

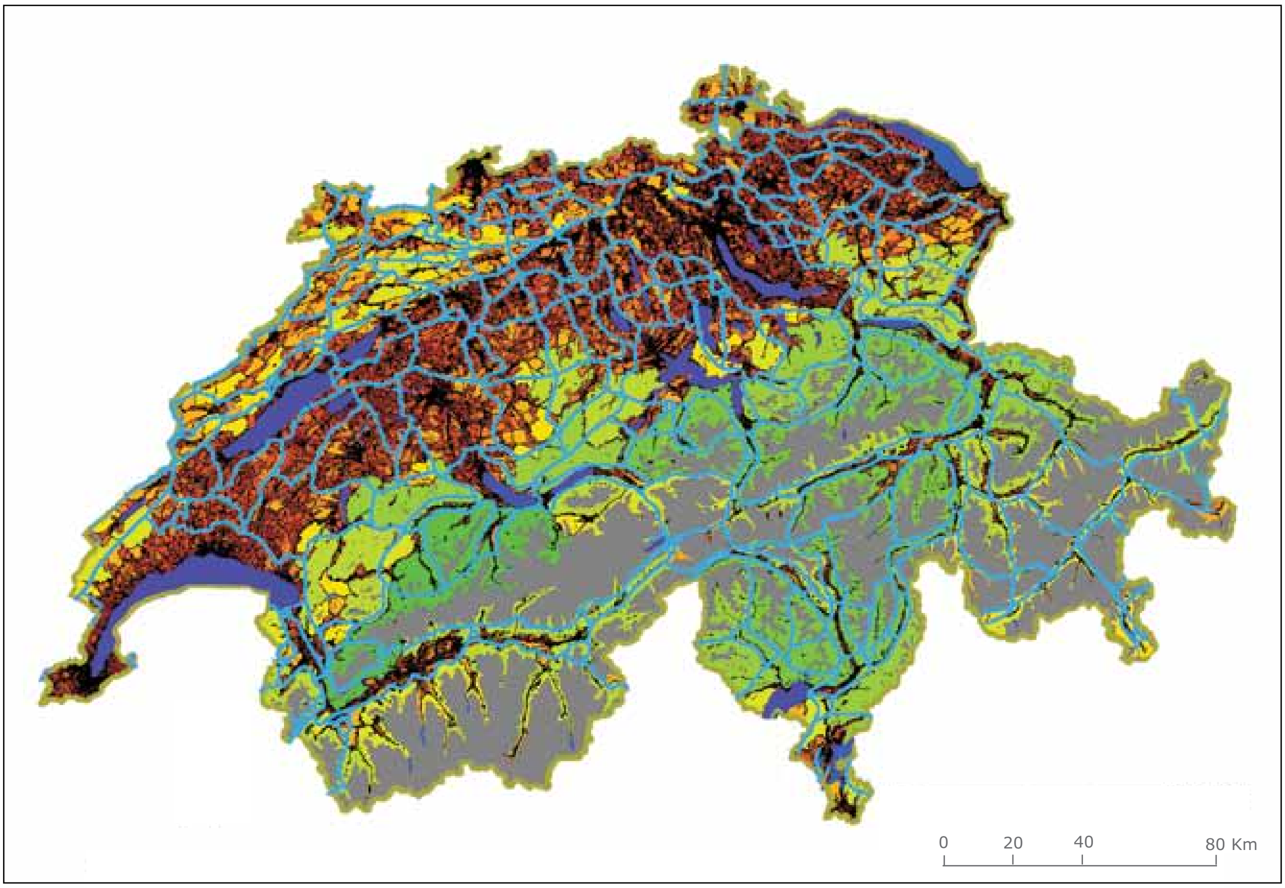
Aargau, Switzerland, is already too high for brown hare populations to persist, and the construction of wildlife passages is not enough to improve the situation for these populations.

4.2.2 *Relevance for biodiversity*

In many parts of Europe, populations of large terrestrial mammals are endangered or the animals live in small numbers, and many of these species have large habitat requirements and require long distance migrations and dispersal (Boitani, 2000; Mysterud et al., 2007). The populations' chances for survival are affected more and more by the number of roads traversing their habitats. In areas where the effective mesh size is smaller than the typical size of the home range of a species, the animals encounter roads and other barriers on a daily basis.

The long response times of many species to changes in landscape structure present a particular challenge. The current population densities may not be the response to the current landscape pattern but to earlier landscape patterns decades ago, and wildlife populations may continue to decline for many years even if the degree of landscape fragmentation does not increase in the future. Given that the negative effects of habitat fragmentation and isolation often only become apparent after several decades, it is likely that further population losses will be incurred in the coming decades as a result of the landscape changes that have already taken place (Findlay and Bourdages, 2000). This lag in the occurrence of extinctions in response to landscape changes has been called an 'extinction debt' (Tilman et al., 1994). If a decline in wildlife populations is documented, it may already be too late to take measures to stabilise the populations, as in the case of brown hare in Aargau Canton, Switzerland (Roedenbeck and Voser, 2008). This makes it all the more essential that a precautionary approach is adopted that guides landscape fragmentation in the desired direction in the next decades, while future research projects should fill the remaining gaps in knowledge.

Map 4.2 **Overlay of the wildlife corridor network of trans-regional importance in Switzerland with the Swiss fragmentation geometry FG4 'Land areas below 2 100 m'**



Wildlife corridor network of trans-regional importance in Switzerland

Size of remaining patches in km²

0–5	11–25	51–100	301–1000	> 2500	Mountains	Built-up areas
6–10	26–50	101–300	1001–2500		Lakes	Wildlife corridor

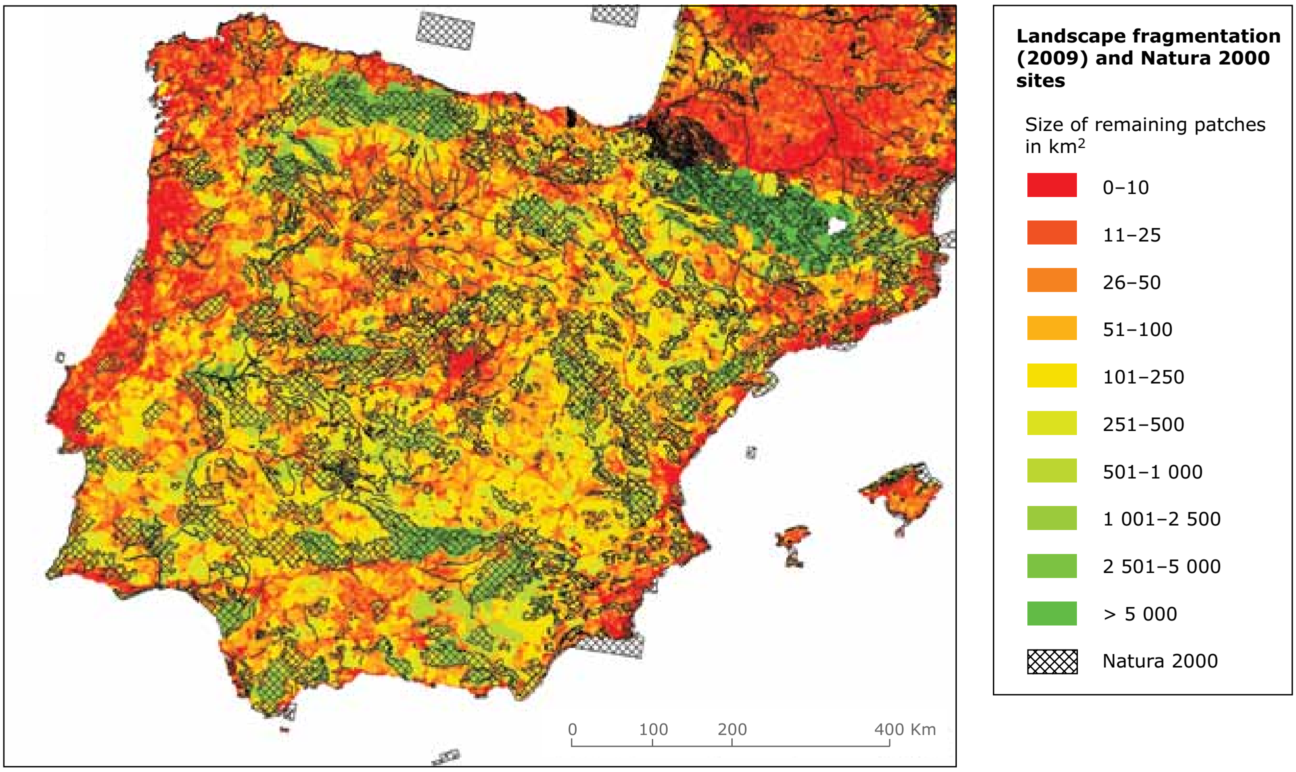
Note: The trans-regional corridor network in Switzerland for terrestrial fauna includes the wildlife corridors and the trans-regional movement axes. Red, yellow and green colours indicate the sizes of the remaining patches.

Source: Bertiller et al., 2007 (after Holzgang et al., 2001).

We recommend drawing up guiding concepts for the landscapes in Europe (together with the Member States) that include the identification of regionally and nationally important unfragmented areas and priority areas for defragmentation. To make these guiding concepts more tangible, it is desirable to adopt appropriate benchmarks or targets for the degree of landscape fragmentation. For example, the German government and the German Conference of Environmental Ministers claimed as an important goal a 'trend reversal in landscape fragmentation and urban sprawl' in Germany (Bundesminister des Innern, 1985; LANA, 1995). To achieve this goal, the German Advisory Council on the Environment (SRU) (1994: 128 Tz 253) recommended the development and implementation of limits and orientation values for changes in landscape structure over time. Waterstraat et al. (1996) recommended the protection of large unfragmented low-traffic areas in Germany. More recently, the German Federal Environment Agency suggested that region-specific limits to control landscape fragmentation should be introduced (Penn-Bressel, 2005).

The maps of the three fragmentation geometries can support the delineation of 'barrier-free corridors' to maintain ecological flows in the landscape (Maps 4.2 and 4.3). Appropriate objectives and measures should be elaborated that are made binding for European and national offices and

Map 4.3 Overlay of the Natura 2000 network with fragmentation geometry FG-A2 'Major and medium anthropogenic fragmentation', showing Spain and Portugal as an example



Note: Many protected areas are located in regions that contain large unfragmented patches. River systems that are protected are visible as black lines. Depending on the particular objectives of a study, differing FGs are most suitable.

Source: EEA/FOEN, 2011.

should state what measures should be taken and where and how they should be implemented, in connection with ongoing EU initiatives for a green infrastructure (Green Infrastructure, 2007). A process of Europe-wide documentation and coordination is recommended to produce an overview of measures at the European level and to enable regional strengths and shortcomings to be recognised more easily. This work could build on the achievements of the previous *EU COST 341 Action* (Iuell et al., 2003) and the *Infra Eco Network Europe* (IENE) (http://www.iene.info).

Continued increase in landscape fragmentation will also increase the future costs for re-connecting separated habitats, for the restoration of wildlife corridors and the rescue of endangered wildlife populations. For example, the map of the wildlife corridors of national importance in Switzerland in Map 4.2 provides an idea of the size of the task of restoring wildlife corridors which will be huge, once the landscape has become heavily fragmented. Therefore, it is wise policy to implement effective measures to avoid an increase of the level of fragmentation from the beginning as much as possible, in particular as it is unknown when the 'point of no return' in the decline of wildlife populations is reached.

Previous research has demonstrated that there are thresholds in the effects of landscape fragmentation on the viability of wildlife populations (Hanski and Ovaskainen, 2002; Jaeger and Holderegger, 2005; Jaeger et al., 2006). Various studies about the effects of landscape fragmentation on biodiversity have been conducted on a smaller scale, e.g. for European badger (*Meles meles*), fox (*Vulpes vulpes*), roe deer (*Capreolus capreolus*) and wild boar (*Sus scrofa*) in Hesse, Germany, by Roedenbeck and Köhler (2006), and for brown hare (*Lepus europaeus*) in Aargau Canton, Switzerland, by Roedenbeck and Voser (2008). Several studies reported values of road density above which certain species do not occur any more (e.g. Mech et al., 1988 for wolves (*Canis lupus*) in Minnesota, Jensen et al. 1986 for wolves in Ontario, Thiel 1985 for wolves in Wisconsin, Mace et al. 1996 for grizzly bears (*Ursus arctos horribilis*) in Montana, reviewed by Switalski, 2006; Fahrig and Rytwinski, 2009; Robinson et al., 2010). A recent study by Sharafi et al. (subm.) showed that lower values of the effective mesh size values strongly correlate with invasion of non-native plant species and reductions in remnant native vegetation. However, to our knowledge, there are no studies so far on the European level because of a lack of data on the degree of landscape fragmentation. Since this report provides the data about the degree of landscape fragmentation in Europe on three scales and for three fragmentation geometries, this task can now be achieved in a follow-up project.

What do these thresholds mean for biodiversity and for traffic planning and nature conservation in Europe? If wildlife populations have so far survived all the new road construction in a landscape, this does **not** imply that the populations will also be able to withstand further densification of the transportation network. When the threshold has been reached, it is highly likely that the next new road will bring about the populations' extinction. Even worse, when the 'point of no return' has been crossed and the population is already in decline, it will be impossible to reverse the trend even if relatively drastic measures were taken. The thresholds will depend on the habitat requirements of the species in question and the number and severity of the barriers. Ecological factors such as the spatial distribution of habitats or a population's birth and mortality rates also influence the thresholds. It is very difficult to consider the effects of all these factors, as this requires large amounts of empirical data for different habitat types over long time periods. Such data can be gathered only in large-scale long-term studies, which are rare. This is why the exact thresholds for a population or a species are largely unknown, and it is unlikely that they will be known any time soon. Therefore, any hopes for a general hard number for the maximum acceptable level of fragmentation will be disappointed. Rather, the precautionary principle should be applied in the assessment of landscape fragmentation, and the implementation of limits requires a consultation process, just as it has been the case with other limits that are in use for water quality and air quality (Streffer et al., 2003).

The important role of large roadless areas for biodiversity conservation has been emphasised in the scientific literature (e.g. DeVelice and Martin 2001; Turner 2006), and it is equally important for preserving landscape quality. The protection of the remaining large unfragmented areas is a measure of high priority and should be implemented immediately, based on the existing maps and existing knowledge about habitat types, habitat amount, and habitat quality. However, conservation efforts should not only be directed towards the protection of the remaining large unfragmented areas, but also to prevent further fragmentation where the landscape is already highly fragmented to preserve biodiversity in these places as well (see also Box 4.2 in Section 4.3.2).

To better consider the internal structure of large unfragmented areas, i.e. the spatial distribution of habitats and functional relationships, Reck et al. (2008) recommended the preservation of **Undissected Functional Areas (UFAs)** (*unzerschnittene Funktionsräume*, UFR) for Germany. This important suggestion should be considered in all places where such data are available. However, it is unclear if this approach will be feasible at the European scale. Where such data are available, the effective mesh density method can be directly applied to these habitat networks because this is where the movements of individuals are known to take place. The resulting values would indicate the degree of fragmentation of these habitat networks rather than the degree of fragmentation of the landscape in general.

The synergistic effects of roads and other factors that operate simultaneously (e.g. agricultural intensification, increased urbanisation) have rarely been investigated. Empirical studies are limited by the delayed response of wildlife to many environmental changes, and wildlife populations will continue to decline for many years (in the order of decades) before they will reach a new equilibrium. This lack of knowledge is often used as a justification for not preventing the construction of new roads or for not including more substantive mitigation measures, by arguing that not enough is known and more research is needed before road construction might slow down. This situation constitutes a 'fragmentation spiral' (Jaeger, 2002), because research has been unable to catch up with the ecological effects of the rapid increase in road densities. This situation flies in the face of the principles of sustainability and is contrary to the precautionary principle. Therefore, there is a danger to think that the addition of wildlife passages to new roads will make it possible to construct new roads without negative consequences to wildlife populations. This attitude would ignore the other negative effects of roads and the critical importance of habitat amount (Fahrig, 2001, 2002).

The **driving forces** of landscape fragmentation and the uncertainties about the ecological effects of road networks tend to be neglected in environmental impact assessments, but they should also be addressed. For example, landscape fragmentation and urban sprawl are aggravated by false incentives: the 'polluter pays' principle is inadequately applied to new developments and to the costs of supplying them with infrastructure; external costs of public and private transport are insufficiently internalised; and when property values increase following planning, development and infrastructure activities, there are no levies. These all send out false signals and make construction in open countryside disproportionately attractive (Frey and Zimmermann, 2005).

According to our results, the most relevant driving force is human population density. Average *GDP* per capita is relevant in some cases, but not always, e.g. it is relevant when the settlement structure is disperse such as in Belgium. However, contrary to our initial hypothesis, if human populations with a high average *GDP* per capita are concentrated in cities, their level of fragmentation tends to be lower with increasing *GDP*c, as is the case in many countries in western Europe (i.e. groups A, B, C).

Fences are often used along highways to increase traffic safety. They protect animals from collisions with vehicles, but they also increase the barrier effect of roads. The outcome of this trade-off for the population depends on traffic volume and the behaviour of the animals at the road, and it is often unclear in what situations fences are an advantage or a disadvantage for wildlife populations. Jaeger and Fahrig (2004) demonstrated that fences can be a suitable measure to slow down the decrease of wildlife populations, but only as an interim answer and not as a permanent solution, and that they need to be combined with wildlife passages (Figure 4.2). Further research is needed before practical conclusions can be drawn.

In order to evaluate the impacts of any new fragmentation element, it is increasingly necessary to consider the network effects beyond the individual construction; in other words, a strategic environmental assessment (SEA) is recommended to determine the cumulative impacts. Here, the application of the effective mesh density method will also come in useful, and it should also be taken into consideration in the development of new long-term concepts for a restructured transport system that does not depend on fossil fuels.

The character of ecological risks associated with landscape fragmentation and the often high uncertainties of the effects make the question of whether such road and railway construction projects are desirable and can be done responsibly difficult to answer. The high level of uncertainty inherent in these ecological risks is reflected by the fact that there is no insurance available for ecological risks (Helten, 1991). It would be desirable to consider introducing an obligatory insurance for such ecological risks to increase the level of accountability for the ecological effects.

4.2.3 Future research needs

There is an urgent need for further research about landscape fragmentation in Europe. The analysis of the relationship between the level of landscape fragmentation and biodiversity is one of the most important areas for future research. For example, the Landscape-Ecological Potential (LEP) already includes the effective mesh size method (Weber et al., 2008), and the LEP can be related to the

Figure 4.2 Two examples of overpasses in combination with fences across a four-lane motorway (left) and a motorway under construction (right) from the Netherlands

Note: The bright stripes on the overpass on the left are trackbeds to record animal tracks crossing the overpass.

Source: Photo left: Rijkswaterstaat, the Netherlands; photo right: Goois Natuurreservaat/W. Metz, the Netherlands.

Community Specialisation Index and other indices of biodiversity ([2]). This research would need to consider the response times of species to the deterioration of their environment ('extinction debt') and therefore, needs to include historic states of the landscapes in Europe. Other important factors such as habitat quality have to be included in the analysis because the relationship between landscape fragmentation and the response variable can be masked when other relevant variables are not included, which can lead to erroneous conclusions (Pope et al., 2000).

Intensively used agricultural fields are also highly fragmenting elements for many species. Therefore, additional fragmentation geometries should be studied in the future that include more fragmenting elements in the landscape, such as agricultural fields, fences, and minor roads (e.g. classes 5 and 6 in TeleAtlas). The consideration of smaller roads is relevant for assessing human access and the spread of invasive species. Therefore, the fragmentation geometries that exclude smaller roads may severely underestimate various ecological effects of the road network on biodiversity. Similarly, electric power lines and other energy infrastructure could be included, which are relevant for some species and for the aesthetic quality of the landscape. Each fragmentation geometry corresponds to a different perspective in which the landscape is investigated. This can be combined with the identification and protection of networks of valuable habitats and landscape linkages (e.g. high nature value farmland and green infrastructure). In addition to the study of particular species, food chains, ecosystems, and ecosystem services should also be considered.

What will the effective mesh density be when the entire transportation infrastructure that is currently in the planning stages in Europe — at least that on the European and national levels — is constructed? Its cumulative effects should be considered in the decision-making process because all these projects will interact and their **combined impact** is relevant for wildlife populations. It is desirable to compare different scenarios of how many and where the new roads and railway lines will be located. Future research studies should also consider other types of reporting units, such as watersheds, ecosystem types (e.g. forests, grasslands, wetlands) and corridor-habitat networks. Species-specific studies can apply the effective mesh density to the habitat of a particular species rather than to the landscape in general, i.e. all non-habitat would be considered as barriers of varying degrees of permeability. Different species perceive the landscape differently, and their respective degrees of habitat fragmentation differ accordingly.

Earlier points in time should be investigated to determine the rate of increase in landscape fragmentation. To include the differing barrier strengths of roads between 0 % and 100 %, the probability of successful road crossings (as a function of traffic volume) and the positive effect of wildlife crossing structures on landscape connectivity can be considered in a more detailed version of the effective mesh density. As the barrier effect of a road and the effectiveness of wildlife passages are species-specific, the values of the effective mesh density would differ between species. Unfortunately, there is a lack of quantitative data about the probability of species to use wildlife crossing structures and the probability of successful highway crossings which depends on traffic volume on the road. The refined version of effective mesh density is available (Jaeger, 2002, 2007) and can be applied once such data can be obtained. Habitat quality of the patches can also be included in the calculation. These refinements would make the calculation of the degree of fragmentation more complicated, and the different values of effective mesh density for different species considered may be too much information for environmental monitoring systems that usually include only one or a small set of indicators of landscape fragmentation.

More in-depth research about the driving forces and improvements to the predictive model of landscape fragmentation are also desirable to gain a better understanding of regions that are clearly much more fragmented than expected or of those that are less fragmented than expected. Additional predictor variables such as historic states of the landscape, the history and enforcement of regulations, subsidies, urban settlement patterns, differences in land-use planning (e.g. existence of regional planning, the degree to which its application is compulsory, and the time since its implementation), and a measure of remoteness of the region should be considered. The statistical analysis could also be refined by including non-linear effects and interaction terms.

The identification of thresholds of landscape fragmentation is a particularly important task. However, the thresholds are likely to depend on

([2]) LEP is an indicator to measure and assess terrestrial ecosystem integrity at large scales in Europe on the basis of land cover changes which is understood as a key determinant of the potential of ecosystems to deliver multiple services necessary for society development and human well-being. It is also under consideration as part of a physical account of the natural capital which can then be used as an adjustment to the GDP (EEA, 2006c).

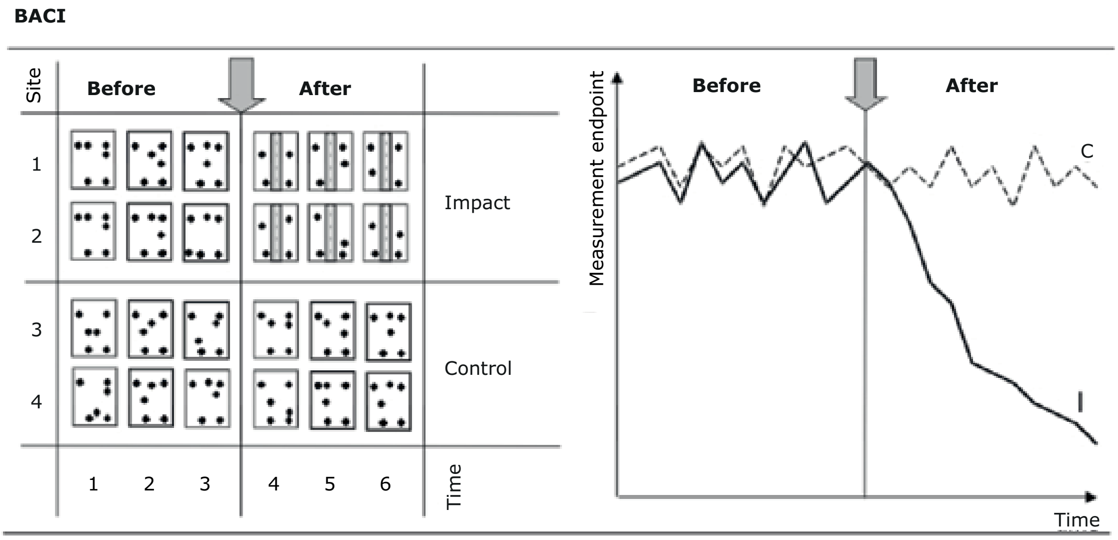
the amount and quality of the remaining habitat in the landscape and on various other factors (other impacts such as pesticides and pollution) that affect wildlife populations **in combination**, which makes the identification of thresholds a challenging task. Notwithstanding its difficulty, this task is important for the future analysis and assessment of cumulative effects in environmental impact assessments and transportation planning and should be investigated in long-term, large-scale scientific studies.

The young research field of road ecology is confronted with many urgent unanswered questions (Roedenbeck et al., 2007; van der Ree et al., 2011). Most importantly, research in road ecology needs to move towards larger scales. There is a paucity of studies that explicitly examine the population, community, ecosystem, or landscape-level effects of roads and mitigation measures. Most of these higher-order effects remain unquantified, and must become the focus of future studies because the complexity and interactions among the effects of roads and traffic are large and potentially unexpected. An analysis of these complex interrelations requires systematic research using the before-after-control-impact (BACI) study design (Figure 4.3), and it is necessary to further establish collaborative links between ecologists and transportation agencies. Many road agencies have 'environmental sustainability' as one of their goals and the only way to achieve such goals is for them to support and foster long-term and credible scientific research. The current situation, with numerous small-scale projects being undertaken independently of each other, cannot provide the information required to quantify and mitigate the negative effects of roads and traffic and the positive effects of mitigation measures on higher levels. The future of road ecology research will be best enhanced when multiple road projects in different states or countries are combined and studied as part of integrated, well-replicated research projects (van der Ree et al., 2011).

In addition, a research approach is required that will address the remaining uncertainties which to a large degree are irreducible, e.g. through building on the precautionary principle (e.g. EEA, 2001) and the concept of environmental threat (Jaeger 2002, Scheringer 2002). This would open up promising new lines of action for landscape management. For example, the German Federal Environment Agency recently suggested that region-specific limits to control landscape fragmentation should be introduced (see Box 4.2). Further research should also address the question of how current transportation systems can be improved to keep landscapes unfragmented.

The fragmentation of rivers and streams by dams is a highly relevant issue for aquatic biodiversity.

Figure 4.3 Illustration of the before-after-control-impact (BACI) study design for investigating the effects of transportation infrastructure on wildlife populations



Note: The rectangles indicate landscapes at various points in time before and after the construction of a road. The black dots in the landscapes indicate the abundance of wildlife species. Measurement endpoint is the variable measured over time, e.g. population density in the landscape. (I = Impact, C = Control).

Source: Roedenbeck et al., 2007.

The current project did not include this topic as it focused on the fragmentation of land areas. An analysis of the fragmentation of water courses requires a separate research effort.

4.3 Recommendations for controlling landscape fragmentation

What measures are suitable and feasible for bringing about a trend reversal in landscape fragmentation? Generally, four types of measures to address the problem of landscape fragmentation can be distinguished: (1) to minimise negative impacts during the planning and construction stages of new transportation infrastructure, (2) to restore connectivity across existing transportation infrastructure, (3) to prevent further increase of the density of the transportation network, and (4) to remove existing transportation infrastructure. This section proposes various measures primarily in relation to the effective mesh density and mesh size. The authors of this report recommend that all these measures be broadly applied in transportation planning and regional planning and their feasibility and effectiveness be evaluated in more detail. Rethinking transport systems to improve their efficiency may be an important component of this. Without better methods and higher awareness and consideration of the remaining uncertainties it will be impossible to resolve the increasing conflicts about land-use and landscape fragmentation in a responsible manner.

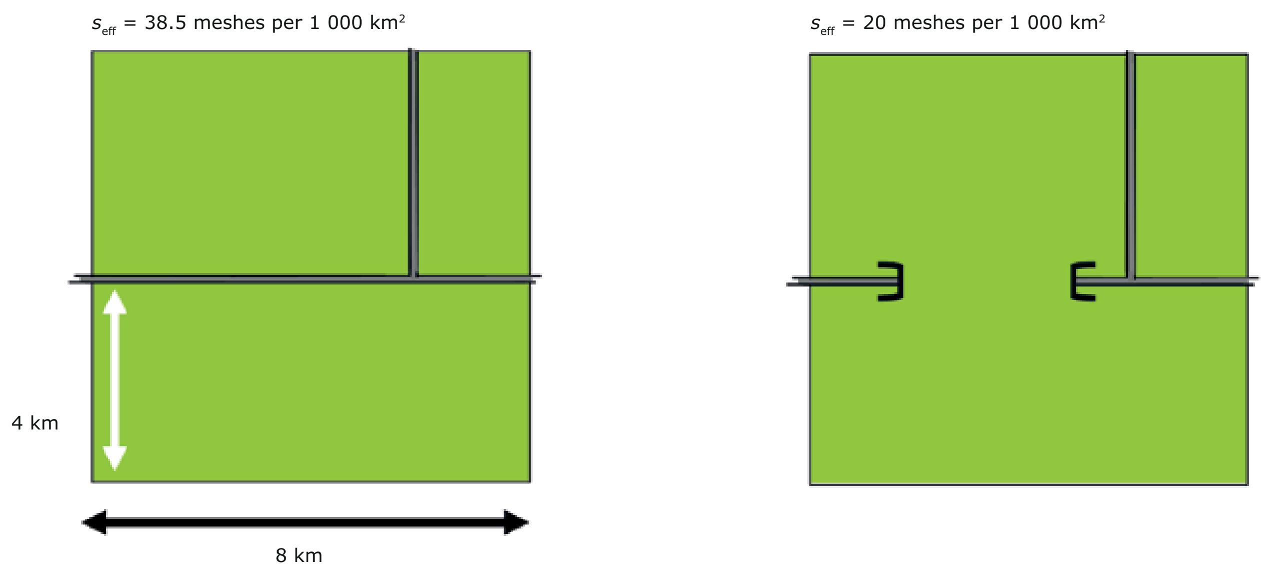
However, this list of measures is not comprehensive. For example, it does not cover measures in the fields of communication and education of the public, economic or market-based instruments, reorganisation of traffic, and promotion of changes in behaviour. In addition, regional differences need to be considered, as highlighted by the six different statistical models for the prediction of the level of landscape fragmentation from Chapter 3 of this report. This implies that different measures may be needed in regions with different current levels of fragmentation, with different departures of the observed from the predicted levels of fragmentation, and with different prevailing driving forces. Thus, the measures may need to be applied in differing combinations to the various regions. When deciding on these measures, the combined effects of a series of measures should be considered.

4.3.1 Measures in traffic planning and regional planning

- **Tunnels and wildlife passages**

Existing roads and railways can be made more permeable for wildlife through tunnels (Figure 4.4), crossing structures (wildlife overpasses and underpasses), or by raising roads up on pillars so that wildlife can cross underneath. In general, the larger the areas linked together, the more effective

Figure 4.4 Illustration of the effect of tunnelling on the effective mesh density



Note: Effective mesh density is lower if the road is routed through a tunnel (right) than without a tunnel (left).

Source: Jaeger et al., 2007.

the measures will be. Therefore, the neighbouring areas and the interactions with other measures should be taken into account in the development of defragmentation plans. This measure can take advantage of the topographic conditions of the landscape (e.g. bridges across streams and valleys).

- **Priority of upgrading of existing roads over construction of new roads**

The widening of existing highways and railways will increase their barrier effect, and higher traffic volumes will contribute to the stronger barrier effect. However, the upgrading of existing highways is still less detrimental than the construction of new highways at another location in most cases, even if the new highways were to be bundled with existing transportation infrastructure. This has been demonstrated by a computer simulation model that determined the probability of population persistence to compare these alternatives (Jaeger et al., 2006). The upgrading of existing highways is an example of making better use of the existing road network and of addressing increased transportation demands while minimising the increase in landscape fragmentation.

- **Bundling of transport routes**

The tighter that transport routes are bundled together, the larger the remaining unfragmented areas of land. If, for example, a railway line is already present, any new road should be planned to run as close and parallel to the existing line as possible (Figure 4.5). The barrier effect of a bundle of transport routes will be higher than the barrier effect of a single transport route, but bundling is usually a better solution than the fragmentation of a larger area. In addition, wildlife passages could then be placed so that all the transport routes could be crossed over or under in one go. In general, an upgrade of existing routes should, however, be preferred, see above.

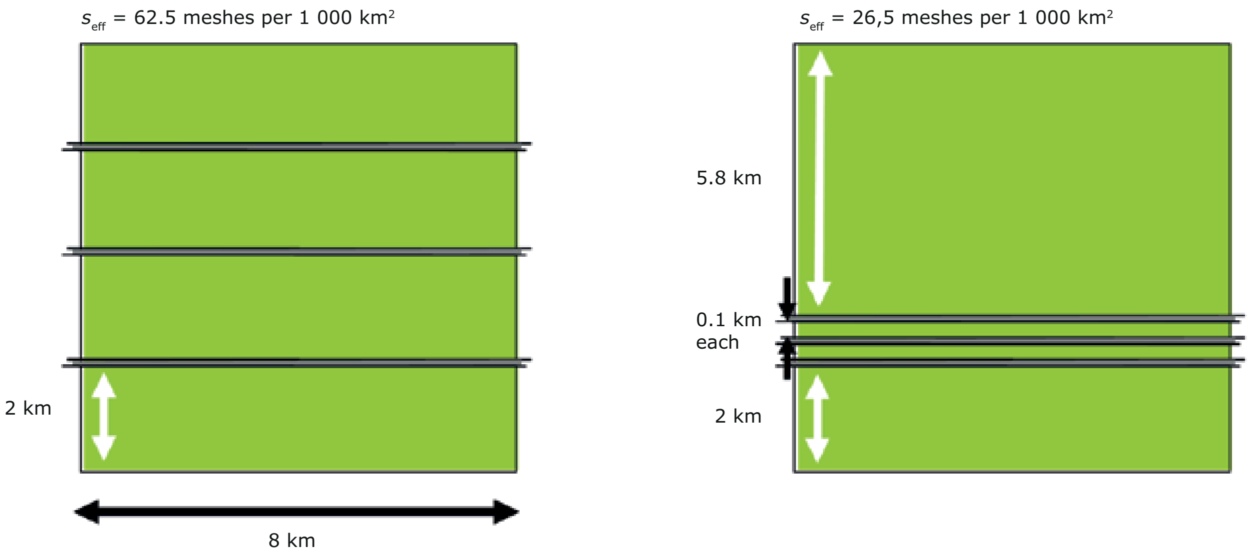
- **Keep bypass routes close to settlement areas**

If bypasses (and other roads) are sited close to developed areas, their fragmentation effect is lower compared to the construction of bypasses away from settlements (Figure 4.6). The purpose of this measure is to preserve unfragmented areas that are as large as possible and to lessen the fragmenting impact of any new transport routes.

- **Dismantling of transportation routes**

Transport infrastructure which is not urgently needed any more (e.g. due to the construction of new routes or changing requirements) should be removed. This is particularly important where existing infrastructure is located in an area of animal movement corridors, e.g. amphibian migration corridors. Currently, actual dismantling of roads that are no longer needed is very rare, and usually

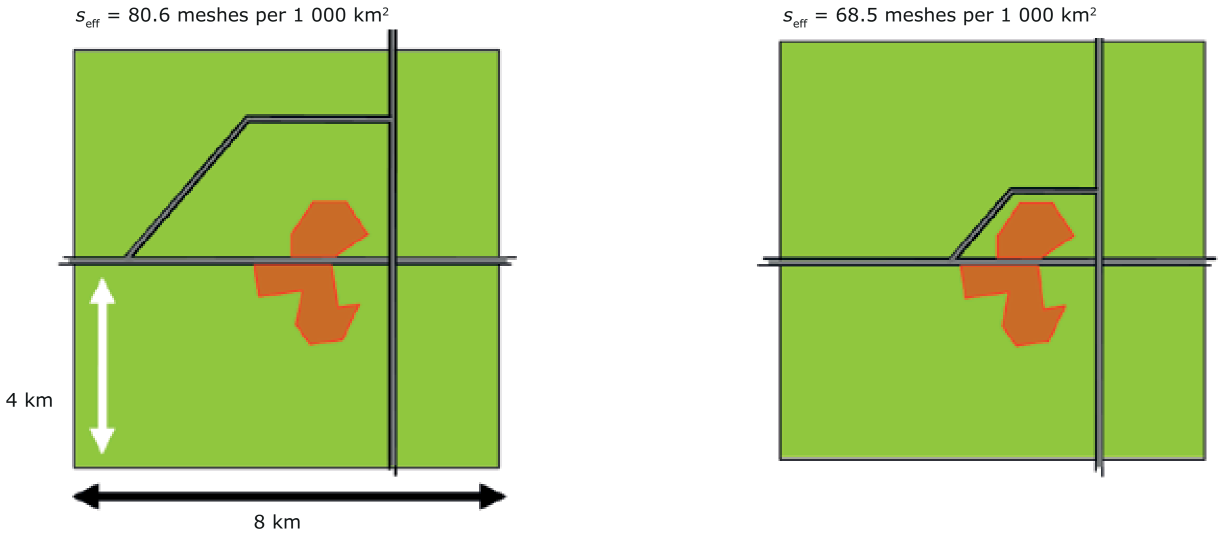
Figure 4.5 Illustration of the effect of bundling transport routes on the effective mesh density



Note: Effective mesh density is lower if the transport routes are bundled (right), than in a regular distribution of routes across the entire landscape (left).

Source: Jaeger et al., 2007.

Figure 4.6 Illustration of the effect of bypass location on the effective mesh density



Note: Effective mesh density is lower if the bypass is drawn tighter around the settlement (right), than if the road is built farther away (left).

Source: Jaeger et al., 2007.

only affects sections of old roads that have been upgraded or moved to the side. The potential for removal of roads is probably higher than the current practice suggests. Removal is essentially the more effective, the larger the areas that will be rejoined, but other criteria such as habitat quality should also be considered.

- **Reduction of the width of roads with decreasing traffic volume**

Roads, on which traffic volumes have decreased due to the construction of other transportation infrastructure or due to changing conditions, should be downgraded and physically reduced in width. This means a reduction of their surface and their footprint on the ground through physical modification.

- **Limiting urban areas, and internal urban development based on densification**

In order to preserve open space in the countryside, it is necessary to limit the size of urban areas. For example, the report *Urban sprawl: Europe's ignored environmental challenge* by the European Environment Agency calls for urgent action and suggests developing Europe-wide policies to curtail urban sprawl (EEA 2006a). This would also help counteract continued landscape fragmentation since built-up areas are themselves barriers to animal movement and contribute to landscape fragmentation, and since urban sprawl and road construction mutually intensify each other: dispersed patterns of settlement areas lead to higher traffic volumes and more road construction, and roads attract urban development. Regional planning legislation should more effectively require local authorities to treat land sparingly in their land-use plans. Regional and local authorities should limit the growth of built-up areas and encourage development within urban areas, e.g. through the reuse of brownfield sites, promoting compact design in developed zones and qualitative improvements of neighbourhoods. Limiting lines and green belts can ensure that clear open spaces are left between built-up areas. Open spaces are also significant in providing linkages for animals and plants as well as in providing local recreation areas.

- **Oasis concept**

The oasis concept is an innovative new idea for designing transport infrastructure. This means that small communities and areas suitable for preserving biodiversity or for recreational use (refuges or 'oases') will be kept free from trans-regional traffic (Arbeitskreis Strassen im VCD-Kreisverband Ludwigsburg, 1996; Jaeger, 2002). Road traffic will be concentrated onto a small number of roads located at a clear distance from such oases. Small communities will be connected by access roads. Current roads that route traffic directly from community to community will then be dismantled.

The major advantages of the concept are that communities are freed from through-traffic, that areas for preserving biodiversity or for recreational use are protected from through-traffic, and that it halts the trend of continually building new bypasses around communities. This concept may prompt new ideas for the planning of new roads. It can also be applied to roads dedicated to agricultural purposes, as part of continued restructuring in the agriculture sector, i.e. when farms are abandoned and the network of agricultural roads can be rearranged.

4.3.2 Measures at a strategic level

- **Preserving and restoring wildlife movement corridors**

The restoration of damaged or severed wildlife corridors is a significant step in recreating the opportunities for species to migrate and disperse. Ongoing efforts for implementing a system of green infrastructure (Green Infrastructure, 2007) aim at addressing this issue on the European level. In many countries, some regulations and instruments can already be used either directly or indirectly to promote defragmentation; for example, protected areas, wildlife corridors/habitat networks, and defragmentation plans. Examples from Switzerland are the **Federal Inventory of Landscapes**, **Natural Sites and Monuments of National Importance** (BLN areas), the **Swiss Landscape Concept** (Bürgi, 1998), the **National Ecological Network** (REN; Berthoud et al., 2004), and a wildlife corridor restoration programme that the Swiss Federal Roads Authority (FEDRO) and the Swiss Federal Office for the Environment (FOEN) have drawn up jointly (**Corridor System for Wildlife in Switzerland**; Holzgang et al., 2001, 2005; UVEK, 2001a, 2001b). However, the first three regulations are very weak instruments that rarely prevent new road projects in practice and would need to be adopted with a stronger political will. Similar projects exist in many other countries in Europe. For Germany, Grau (2005) provided an overview of existing programmes on defragmentation on the federal and state level, and suggested a hierarchical approach to defragmentation planning. This survey documented nine country-wide and 13 state-wide studies and programmes, planned or already in existence, that mapped potential corridors and barriers for wildlife. These studies varied greatly in method and scale, ranging from ideas and concepts to tangible action plans. Perhaps the most prominent country-wide plan is the **German Habitat Corridor Network** (Reck et al., 2005; Böttcher et al., 2005; Hänel and Reck, 2011). An example from the Netherlands is the Dutch **Long-Term Defragmentation Programme** (van der Grift, 2005). A similar approach was recently applied to Bulgaria to assess priority spots for defragmentation measures based on the Dutch LARCH model (van der Grift et al., 2008).

However, these wildlife corridor plans do not match well along the boundaries between different countries. Therefore, better coordination of these efforts at the European level is needed.

- **A European defragmentation strategy**

Landscape fragmentation must no longer continue to increase within trans-regionally important wildlife corridors. Rather, transport infrastructure that is not absolutely necessary should be removed or tunnelled under or bridged over. Likewise, built-up areas should be strictly prevented from expanding in these areas.

Various ecological network initiatives exist on the European level (e.g. Tillmann, 2005). Four important examples are:

- the **Pan-European Ecological Network** (PEEN) under the aegis of the Council of Europe (CE), the United Nations Environmental Programme (UNEP) and the European Centre of Nature Conservation (ECNC) (Jongman et al., 2011);
- the network **Natura 2000**, established by the EU Habitats and Birds Directives, comprising Special Areas of Conservation (SAC) of the Habitats Directive (92/43/EEC, 1992) and Special Protection Areas (SPA) of the EU Birds Directive (79/409/EEC, 1979);
- the **Emerald Network**, also known as **Network of Areas of Special Conservation Interest**, launched in 1989 by the CE (Council of Europe, 2009); and
- the **Trans-European Wildlife Networks Project** (TEWN) (EuroNatur, 2010).

The Natura 2000 and Emerald networks are based on the same idea, but EU Member States design Natura 2000 sites, while non-EU countries designate Emerald sites (e.g. Norway, Switzerland, Turkey). The establishment of climate change adaptation networks, largely based on national networks, is likely to gain importance in the future.

Ideally, the PEEN should integrate all network initiatives. The PEEN will consist of core areas, corridors and buffer zones and will identify restoration areas where they are considered necessary. It aims to conserve the full range of ecosystems, habitats, species and landscapes of European importance and to counteract the main causes for decline by creating the right spatial and environmental conditions (Council of Europe, 1996). These initiatives that aim at preserving biodiversity should be enhanced by indicating the locations where defragmentation measures should be implemented for the restoration of wildlife corridors.

However, the impact of the existing initiatives has been rather low. The current Natura 2000 system is highly fragmented and represents an unconnected set of unevenly protected 'islands' (Map 4.3). Even though there is a strong legal instrument for establishing the Natura 2000 system in EU Member States, this mandate has still not been sufficiently implemented by the countries. The Natura 2000 system needs to be developed into a system of green infrastructure (Green Infrastructure, 2007).

Better coordination is needed to address the challenges of designating trans-boundary wildlife corridors since there still is no responsible institution or coordination mechanism in place (Jongman et al., 2011). Therefore, Tillmann (2005) recommended the creation of an international forum based on an initiative at the European scale as a *COST Action* (*COST* = Cooperation in the field of Scientific and Technical Research) to facilitate cooperation for the designation of trans-boundary ecological corridors. The implementation of a European defragmentation strategy would greatly contribute to this goal and also to the objective of making better use of the existing road network rather than constructing more roads.

- **Effective protection of remaining large unfragmented areas**

The protection of the remaining large unfragmented areas is a measure of high priority and we recommend it to be implemented immediately, based on the existing maps and existing knowledge about habitat types, habitat amount, and habitat quality. These areas should cover habitats of a range of species. The maps can help identify areas where further fragmentation is an imminent threat and their rapid preservation is critical.

This task is particularly urgent in regions with a rapid pace of development, such as large parts of the eastern European countries. In these regions where there are still significant amounts of large unfragmented areas and important pockets of biodiversity left, the mistakes that many regions in the western European countries have committed should not be repeated. Rather, these regions should avoid these mistakes. The fact that many regions in eastern and central Europe and the Baltic countries still have relatively low levels of landscape fragmentation today does not mean that developing further traffic infrastructure to catch up with regions in western Europe is unproblematic. The fragmentation values of the latter regions are among the highest in the world, and other regions should not copy this model that has been shown to be highly detrimental to wildlife populations. The countries in eastern, central and northern Europe hold most of the remaining megafauna in the continent along with the highest levels of endemisms (EuroNatur, 2010). The importance of this measure in the eastern European countries is clear when the many new roads and railways that are planned in these countries are included in the fragmentation analysis. Therefore, maps of the future values of s_{eff} and of the expected increase in s_{eff} should be prepared in a follow-up project.

- **Targets and limits**

There is very little knowledge available about the question where the exact threshold for a particular population is, and by how much the threshold will shift due to diminishing resources, reduced genetic exchange, or changes in climate. Ecological factors, such as the spatial distribution of habitats or changes in a population's birth or mortality rates may also influence these thresholds. A particular challenge is given by the long response times of long-lived animals to changes in landscape structure. This situation makes it all the more essential that a precautionary approach is adopted that guides landscape fragmentation in the desired direction. The lack of knowledge about the exact location of the thresholds should not be used as an argument for postponing protective measures. Rather, targets and limits for the future degree of landscape fragmentation should be broadly discussed and implemented. Such targets and limits are urgently needed by government offices and administrations for being able to act and for justifying their decisions and actions towards better protection of the environment. An example is given in Box 4.2. This measure will contribute to making better use of the existing road network rather than constructing new roads. These limits cannot be set in stone but should be region-specific and should consider the ecological, geographic, social, economic, and historic characteristics of each region. The socioeconomic models presented in this report can support the definition of these limits.

For example, specific targets, benchmarks and limits could be distinguished according to the respective type of landscape:

1. Priority regions for large unfragmented areas; i.e. no further fragmenting elements are allowed here, and there is a priority for the removal of existing fragmenting elements.

2. Setting of targets for rural landscapes.

3. Further fragmenting elements could be allowed in densely settled landscapes or along of development axes up to a certain limit.

Considering the data about landscape fragmentation in 28 European countries presented in this report and the available method for quantifying the degree of fragmentation, the implementation of targets and limits seems to be feasible in a medium-term horizon. The values decided upon can be revised at a later point in time when knowledge about the effects of landscape fragmentation will have increased. As long as the knowledge about the thresholds of landscape fragmentation is insufficient, the precautionary principle should be applied (Kriebel et al., 2001). A more detailed discussion of limits to landscape fragmentation is given in Jaeger (2001, 2002) and Bertiller et al. (2007).

4.4 Immediate priorities

The current trend of continued increase of landscape fragmentation is clearly in contradiction to the principles of sustainability, and there is an urgent need for action on the European level as well as on the national level. What are the most urgent priorities for policymaking that the European Environment Agency and its member countries

Box 4.2 Example of a recommendation for limiting landscape fragmentation

The German Federal Environment Agency has issued recommendations for limiting landscape fragmentation based on the effective mesh size (Umweltbundesamt, 2003; Penn-Bressel, 2005). Considering predicted increases in landscape fragmentation, the agency recommended to curtail the rate of increase in Germany. The remaining large unfragmented areas are to be preserved and enlarged where possible; and in areas that are already highly fragmented, the trend is to be slowed down (Table 4.1). By 2015, the reduction in effective mesh size in highly fragmented areas should be at least half the rate had the situation been left unchecked. The following specific aims were set:

1. 'The number and total area of each, as yet, unfragmented, low-traffic areas above 140, 120, 100, 80 and 60 square kilometres shall not decrease further and instead will be increased through defragmentation measures so that their current proportion of 20.6 % of Germany's territory will be raised to 23 % by 2015.

2. The degree of fragmentation of highly fragmented regions shall be limited by additional criteria [as listed in Table 4.1]' (Penn-Bressel, 2005).

The authors of the current report support this recommendation.

Table 4.1 Values for limiting the rate of increase of landscape fragmentation in highly fragmented regions in Germany, as put forward by the German Federal Environment Agency

Starting point at the end of 2002: value of the effective mesh size (m_{eff})	Goal to be reached by 2015: further decrease in effective mesh size (m_{eff}) to be less than:
< 10 km^2	1.9 %
10–20 km^2	2.4 %
20–35 km^2	2.8 %
> 35 km^2	3.8 %

Note: The maximum size of reporting units should not be larger than 7 000 km^2 (for details, see Umweltbundesamt, 2003 and Penn-Bressel, 2005).

should promote? The authors of this report recommend putting into practice the following three measures with highest priority:

- **Immediate protection of large unfragmented areas, ecologically significant areas, and wildlife corridors:** The remaining large unfragmented areas, ecologically significant areas, and functional wildlife corridors should be protected immediately from further fragmentation by adding appropriate criteria and rules to the existing networks of protected areas, such as Natura 2000 and Emerald networks, national parks, and green infrastructure corridors. Critical areas should be identified where further fragmentation is an imminent threat and their rapid preservation is crucial before they would be lost to fragmentation by roads and railroads. This task is particularly urgent in regions with a rapid pace of development, such as large parts of the eastern and central European countries. The mistakes that many regions in the western European countries have committed should not be repeated by other regions. This is most essential in regions that still have important pockets of biodiversity. Ongoing increase in landscape fragmentation will also increase the future costs for the restoration of wildlife corridors and habitats and for the rescue of endangered wildlife populations. Therefore, it is wise policy to implement protective measures from the beginning to avoid an increase of the level of fragmentation as much as possible. Policymaking on the European level has an important responsibility to advance this urgent need for action when funding for transportation infrastructure is provided. The provision of funds for transportation infrastructure should be strictly linked to the requirement of protecting the remaining unfragmented areas in these regions. In addition, possible avenues for implementing targets, benchmarks and limits for the future degree of landscape fragmentation should be considered as a new policy (see above).

- **Monitoring of landscape fragmentation:** Landscape fragmentation is an essential indicator of threats to biodiversity, to the sustainability of human land-use, and to landscape quality. It should be implemented in monitoring systems of biodiversity, sustainable development, and landscape quality. Tracking the changes in landscape fragmentation on a regular basis is a precondition for being able to diagnose the rate of increase and changes in trends.

- **Application of fragmentation analysis as a tool in transportation planning and regional planning:** The cumulative effects of new transportation infrastructure on the degree of landscape fragmentation should be analysed quantitatively and in more detail in the planning process. The effective mesh density method should be included in the planning process as an instrument for this task, in combination with other relevant criteria (such as habitat amount and quality), e.g. to compare alternative transportation corridors for new roads and railway lines. This should be a requirement for all transportation infrastructure to which the EU provides some financial support. This task is particularly important because these roads and railroads have strong disturbance effects. In addition, the uncertain effects of landscape fragmentation need to be considered more seriously and studied more systematically, e.g. through the use of the before-after-control-impact (BACI) study design (see above).

Large unfragmented areas are a limited and non-renewable resource. This fact is particularly important to consider in Europe, where high human population densities compete for land with biodiversity. Land and soils are finite and their destruction is irreversible within human life spans. Renewable energy supply requires large tracts of land, food production necessitates arable and pasture land with suitable soils, and land is also needed for urban-industrial purposes, transport, resource extraction, refuse deposition, and recreation, i.e. all of them compete for land. As a consequence, mankind's growing demands for renewable energy, food, and land cannot be circumvented by any form of adaptation. Haber (2007) has called these growing demands the three major 'ecological traps' that threaten mankind probably more severely than any other environmental problem. If endeavours for promoting sustainable development disregard these three ecological traps, they will inevitably miss their goals. As a consequence of these growing demands, the remaining unfragmented areas are under an enormous pressure. Therefore, much higher efforts are now required to conserve unfragmented landscapes.

Acronyms

AIC	Akaike information criterion
ARE	Federal Office for Spatial Development, Switzerland
ATKIS	Amtliches Topographisch-Kartographisches Informationssystem (Authoritative Real State Cadastre Information System), used in Germany
BAFU	Federal Office for the Environment (FOEN), Switzerland
BFS	Swiss Federal Statistical Office (FSO), Switzerland
BLN	Federal Inventory of Landscapes, Natural Sites and Monuments of National Importance in Switzerland
CORINE	Coordination of Information on the Environment: European land cover data
EEA	European Environment Agency
*ED*c	education per capita
*EE*c	environmental expenditure of the public sector per capita
ESPON	European Observation Network for Territorial Development and Cohesion
FG	fragmentation geometry
FOEN	Federal Office for the Environment (FOEN), Switzerland
*GDP*c	gross domestic product per capita
GLM	general linear models
Hills	percentage of hills in a region
IsI	island size index
LABES	Swiss Landscape Monitoring Network
LEAC	land and ecosystem accounting
m_{eff}	effective mesh size (measured in km^2) (measure of the degree of landscape connectivity)
MONET	monitoring system of sustainable development in Switzerland
MtSl	percentage of mountains and slopes
NUTS-X	Nomenclature of territorial units for statistics
PD	population density
PPS	purchasing power standard
*QGLU*c	quantity of goods loaded and unloaded in a region per capita
s_{eff}	effective mesh density (measured in effective number of meshes per km^2) (measure of the degree of landscape fragmentation)
TEN-T	trans-European transport network
UR	unemployment rate
VPD	volume passenger density

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Annex 1 Values of effective mesh size and effective mesh density

Values of effective mesh size and effective mesh density for the countries for fragmentation geometry B2 'Fragmentation of non-mountainous land areas'

Country		m_{eff} in 2009 (km²)	s_{eff} in 2009 (number of meshes per 1 000 km²)
AT	Austria	161.31	6.20
BE	Belgium	9.51	105.11
BG	Bulgaria	246.83	4.05
CH	Switzerland	76.59	13.06
CZ	Czech Republic	44.16	22.64
DE	Germany	23.46	42.63
DK	Denmark	62.95	15.89
EE	Estonia	108.36	9.23
ES	Spain	181.22	5.52
FI	Finland	1 443.39	0.69
FR	France	33.84	29.55
GR	Greece	308.22	3.24
HU	Hungary	106.84	9.36
IE	Ireland	170.41	5.87
IT	Italy	111.73	8.95
LI	Liechtenstein	197.73	5.06
LT	Lithuania	75.62	13.22
LU	Luxembourg	7.40	135.17
LV	Latvia	112.93	8.86
MT	Malta	10.20	98.04
NL	Netherlands	16.36	61.12
NO	Norway	2 525.04	0.40
PL	Poland	57.63	17.35
PT	Portugal	108.57	9.21
RO	Romania	1 655.72	0.60
SE	Sweden	1 673.51	0.60
SI	Slovenia	100.85	9.92
SK	Slovakia	209.92	4.76
UK	United Kingdom	265.16	3.77
All 29 countries listed above combined		**573.10**	**1.75**

Values of effective mesh size and effective mesh density for NUTS-X regions for fragmentation geometry B2 'Fragmentation of non-mountainous land areas'

Name	m_{eff} 2009 (km²)	s_{eff} 2009 (number of meshes per 1 000 km²)
(AT) Austria		
Burgenland (AT11)	72.65	13.76
Kärnten (AT21)	200.64	4.98
Niederösterreich (AT12)	56.40	17.73
Oberösterreich (AT31)	135.01	7.41
Salzburg (AT32)	180.15	5.55
Steiermark (AT22)	267.28	3.74
Tirol (AT33)	236.35	4.23
Vorarlberg (AT34)	483.39	2.07
Wien (AT13)	10.47	95.51
(BE) Belgium		
Prov. Antwerpen (BE21)	9.25	108.06
Prov. Brabant Wallon (BE31)	5.91	169.07
Prov. Hainaut (BE32)	7.64	130.96
Prov. Liege (BE33)	14.41	69.40
Prov. Limburg (BE22)	8.97	111.48
Prov. Luxembourg (BE34)	13.72	72.89
Prov. Namur (BE35)	12.29	81.37
Prov. Oost-Vlaanderen (BE23)	5.35	187.04
Prov. Vlaams-Brabant (BE24)	3.29	303.93
Prov. West-Vlaanderen (BE25)	7.15	139.94
Région de Bruxelles-Capitale (BE10)	0.73	1 371.47
(BG) Bulgaria		
Blagoevgrad (BG213)	454.66	2.20
Burgas (BG231)	294.21	3.40
Dobrich (BG132)	201.65	4.96
Gabrovo (BG124)	123.55	8.09
Haskovo (BG223)	352.71	2.84
Kardzhali (BG226)	1 054.97	0.95
Kyustendil (BG215)	135.79	7.36
Lovech (BG122)	194.71	5.14
Montana (BG112)	255.34	3.92
Pazardzhik (BG224)	121.60	8.22
Pernik (BG214)	88.16	11.34
Pleven (BG121)	97.65	10.24
Plovdiv (BG221)	199.00	5.03
Razgrad (BG135)	67.39	14.84

Name	m_{eff} 2009 (km²)	s_{eff} 2009 (number of meshes per 1 000 km²)
Ruse (BG125)	66.32	15.08
Shumen (BG133)	111.90	8.94
Silistra (BG136)	99.29	10.07
Sliven (BG232)	136.93	7.30
Smolyan (BG225)	1 455.61	0.69
Sofia (BG212)	159.94	6.25
Sofia (stolitsa) (BG211)	137.96	7.25
Stara Zagora (BG222)	128.22	7.80
Targovishte (BG134)	81.50	12.27
Varna (BG131)	105.88	9.44
Veliko Tarnovo (BG133)	107.07	9.34
Vidin (BG111)	270.45	3.70
Vratsa (BG113)	121.70	8.22
Yambol (BG233)	355.40	2.81
(CH) Switzerland		
Espace Mittelland (CH02)	59.70	16.75
Nordwestschweiz (CH03)	11.67	85.69
Ostschweiz (CH05)	136.95	7.30
Région lémanique (CH01)	33.79	29.59
Ticino (CH07)	191.87	5.21
Zentralschweiz (CH06)	71.58	13.97
Zürich (CH04)	31.53	31.72
(CZ) Czech Republic		
Hlavni mesto Praha (CZ010)	3.98	251.48
Jihocesky kraj (CZ031)	53.18	18.80
Jihomoravsky kraj (CZ062)	29.91	33.43
Karlovarsky kraj (CZ041)	76.86	13.01
Kralovehradecky kraj (CZ052)	44.40	22.52
Liberecky kraj (CZ051)	52.29	19.12
Moravskoslezsky kraj (CZ080)	79.70	12.55
Olomoucky kraj (CZ071)	69.93	14.30
Pardubicky kraj (CZ053)	17.93	55.77
Plzensky kraj (CZ032)	43.76	22.85
Stredocesky kraj (CZ020)	22.29	44.86

Name	m_{eff} 2009 (km²)	s_{eff} 2009 (number of meshes per 1 000 km²)
Ustecky kraj (CZ042)	25.39	39.39
Vysocina (CZ061)	16.56	60.39
Zlinsky kraj (CZ072)	99.82	10.02
(DE) Germany		
Arnsberg (DEA5)	15.64	63.94
Berlin (DE30)	2.46	405.88
Brandenburg-Nordost (DE41)	33.15	30.17
Brandenburg-Südwest (DE42)	34.80	28.74
Braunschweig (DE91)	24.79	40.34
Bremen (DE50)	8.66	115.42
Chemnitz (DED1)	14.88	67.20
Darmstadt (DE71)	16.86	59.31
Dessau (DEE1)	27.76	36.02
Detmold (DEA4)	9.48	105.46
Dresden (DED2)	18.22	54.88
Düsseldorf (DEA1)	6.16	162.43
Freiburg (DE13)	26.33	37.98
Gießen (DE72)	15.10	66.21
Halle (DEE2)	19.26	51.92
Hamburg (DE60)	3.57	280.19
Hannover (DE92)	19.51	51.26
Karlsruhe (DE12)	17.83	56.07
Kassel (DE73)	18.76	53.30
Koblenz (DEB1)	16.74	59.74
Köln (DEA2)	9.11	109.72
Leipzig (DED3)	11.67	85.69
Lüneburg (DE93)	26.51	37.72
Magdeburg (DEE3)	38.43	26.02
Mecklenburg-Vorpommern (DE80)	33.45	29.90
Mittelfranken (DE25)	8.12	123.09
Münster (DEA3)	9.77	102.40
Niederbayern (DE22)	26.88	37.20
Oberbayern (DE21)	59.58	16.78
Oberfranken (DE24)	12.96	77.16
Oberpfalz (DE23)	23.60	42.37
Rheinhessen-Pfalz (DEB3)	18.26	54.76
Saarland (DEC0)	10.38	96.34
Schleswig-Holstein (DEF0)	13.91	71.89
Schwaben (DE27)	43.18	23.16
Stuttgart (DE11)	11.57	86.39
Thüringen (DEG0)	26.07	38.36
Trier (DEB2)	14.09	70.97

Name	m_{eff} 2009 (km²)	s_{eff} 2009 (number of meshes per 1 000 km²)
Tübingen (DE14)	14.07	71.06
Unterfranken (DE26)	21.98	45.50
Weser-Ems (DE94)	15.61	64.04
(DK) Denmark		
Bornholms amt (DK007)	38.05	26.28
Frederiksborg amt (DK003)	29.84	33.51
Fyns amt (DK008)	54.13	18.47
Kobenhavn og Frederiksberg kommuner (DK001)	1.08	929.52
Kobenhavns amt (DK002)	20.27	49.33
Nordjyllands amt (DK00F)	64.18	15.58
Ribe amt (DK00A)	92.76	10.78
Ringkobing amt (DK00C)	88.59	11.29
Roskilde amt (DK004)	43.36	23.06
Sonderjyllands amt (DK009)	41.02	24.38
Storstroms amt (DK006)	60.97	16.40
Vejle amt (DK00B)	51.30	19.49
Vestsjμllands amt (DK005)	65.76	15.21
Viborg amt (DK00E)	73.75	13.56
Århus amt (DK00D)	61.21	16.34
(EE) Estonia		
Kesk-Eesti (EE006)	105.09	9.52
Kirde-Eesti (EE007)	174.07	5.74
Lääne-Eesti (EE004)	129.16	7.74
Lõuna-Eesti (EE008)	74.15	13.49
Põhja-Eesti (EE001)	132.48	7.55
(ES) Spain		
Albacete (ES421)	137.52	7.27
Alicante (ES521)	60.40	16.56
Almeria (ES611)	227.90	4.39
Asturias (ES120)	374.49	2.67
Avila (ES411)	135.89	7.36
Badajoz (ES431)	149.21	6.70
Barcelona (ES511)	77.31	12.93
Burgos (ES412)	94.13	10.62
Caceres (ES432)	180.88	5.53
Cadiz (ES612)	257.93	3.88
Cantabria (ES130)	230.17	4.34
Castellon (ES522)	191.30	5.23

Name	m_{eff} 2009 (km²)	s_{eff} 2009 (number of meshes per 1 000 km²)
Ciudad Real (ES422)	342.54	2.92
Cordoba (ES613)	247.77	4.04
Cuenca (ES423)	140.36	7.12
Girona (ES512)	194.38	5.14
Granada (ES614)	229.16	4.36
Guadalajara (ES424)	116.59	8.58
Guipzcoa (ES212)	154.60	6.47
Huelva (ES615)	221.63	4.51
Huesca (ES241)	236.07	4.24
Islas Baleares (ES530)	50.91	19.64
Jaen (ES616)	738.20	1.35
La Coruña (ES111)	23.31	42.90
La Rioja (ES230)	253.01	3.95
Las Palmas (ES701)	122.18	8.18
Leon (ES413)	215.54	4.64
Líava (ES211)	114.10	8.76
Lleida (ES513)	283.06	3.53
Lugo (ES112)	74.11	13.49
Madrid (ES300)	53.75	18.60
Malaga (ES617)	164.42	6.08
Murcia (ES620)	133.94	7.47
Navarra (ES220)	197.16	5.07
Ourense (ES113)	187.12	5.34
Palencia (ES414)	83.81	11.93
Pontevedra (ES114)	32.83	30.46
Salamanca (ES415)	104.27	9.59
Santa Cruz de Tenerife (ES702)	75.16	13.30
Segovia (ES416)	67.58	14.80
Sevilla (ES618)	168.25	5.94
Soria (ES417)	121.44	8.23
Tarragona (ES514)	154.53	6.47
Teruel (ES242)	177.15	5.64
Toledo (ES425)	144.21	6.93
Valencia (ES523)	133.93	7.47
Valladolid (ES418)	55.48	18.02
Vizcaya (ES213)	68.72	14.55
Zamora (ES419)	83.46	11.98
Zaragoza (ES243)	203.57	4.91
(FI) Finland		
Åland (FI200)	89.97	11.11
Etelä-Karjala (FI187)	79.56	12.57
Etelä-Pohjanmaa (FI194)	109.30	9.15
Etelä-Savo (FI131)	80.11	12.48
Itä-Uusimaa (FI182)	43.49	22.99

Name	m_{eff} 2009 (km²)	s_{eff} 2009 (number of meshes per 1 000 km²)
Kainuu (FI134)	383.17	2.61
Kanta-Häme (FI184)	60.21	16.61
Keski-Pohjanmaa (FI1A1)	288.73	3.46
Keski-Suomi (FI193)	123.48	8.10
Kymenlaakso (FI186)	79.89	12.52
Lappi (FI1A3)	4 418.31	0.23
Päijät-Häme (FI185)	53.35	18.74
Pirkanmaa (FI192)	80.43	12.43
Pohjanmaa (FI195)	77.79	12.86
Pohjois-Karjala (FI133)	288.91	3.46
Pohjois-Pohjanmaa (FI1A2)	346.91	2.88
Pohjois-Savo (FI132)	101.97	9.81
Satakunta (FI191)	70.48	14.19
Uusimaa (FI181)	37.36	26.77
Varsinais-Suomi (FI183)	45.29	22.08
(FR) France		
Ain (FR711)	20.76	48.17
Aisne (FR221)	11.78	84.87
Allier (FR721)	14.41	69.40
Alpes-de-Haute-Provence (FR821)	165.75	6.03
Alpes-Maritimes (FR823)	487.56	2.05
Ardèche (FR712)	41.27	24.23
Ardennes (FR211)	22.47	44.50
Ariège (FR621)	61.34	16.30
Aube (FR212)	17.10	58.48
Aude (FR811)	35.68	28.03
Aveyron (FR622)	28.99	34.49
Bas-Rhin (FR421)	22.07	45.31
Bouches-du-Rhône (FR824)	38.86	25.73
Calvados (FR251)	6.78	147.49
Cantal (FR722)	34.93	28.63
Charente (FR531)	8.06	124.13
Charente-Maritime (FR532)	9.93	100.70
Cher (FR241)	17.64	56.69
Corrèze (FR631)	15.93	62.77
Corse-du-Sud (FR831)	170.05	5.88
Cóte-d'Or (FR261)	20.63	48.47
Côtes-d'Armor (FR521)	16.16	61.88
Creuse (FR632)	13.92	71.84
Deux-Sèvres (FR533)	15.13	66.07
Dordogne (FR611)	22.46	44.52

Name	m_{eff} 2009 (km²)	s_{eff} 2009 (number of meshes per 1 000 km²)
Doubs (FR431)	24.00	41.67
Drôme (FR713)	209.59	4.77
Essonne (FR104)	7.64	130.94
Eure (FR231)	11.71	85.42
Eure-et-Loir (FR242)	5.17	193.30
Finistère (FR522)	21.39	46.75
Gard (FR812)	23.42	42.70
Gers (FR624)	18.28	54.70
Gironde (FR612)	55.89	17.89
Haute-Corse (FR832)	219.20	4.56
Haute-Garonne (FR623)	17.11	58.45
Haute-Loire (FR723)	23.31	42.90
Haute-Marne (FR214)	22.79	43.88
Hautes-Alpes (FR822)	115.89	8.63
Haute-Saône (FR433)	20.00	50.00
Haute-Savoie (FR718)	41.34	24.19
Hautes-Pyrénées (FR626)	57.55	17.38
Haute-Vienne (FR633)	13.83	72.31
Haut-Rhin (FR422)	27.21	36.75
Hauts-de-Seine (FR105)	0.33	3 047.94
Hérault (FR813)	28.39	35.22
Ille-et-Vilaine (FR523)	10.92	91.60
Indre (FR243)	14.14	70.72
Indre-et-Loire (FR244)	18.43	54.26
Isère (FR714)	114.86	8.71
Jura (FR432)	24.28	41.19
Landes (FR613)	61.01	16.39
Loire (FR715)	16.83	59.42
Loire-Atlantique (FR511)	15.45	64.72
Loiret (FR246)	21.87	45.72
Loir-et-Cher (FR245)	21.86	45.75
Lot (FR625)	16.54	60.46
Lot-et-Garonne (FR614)	24.57	40.70
Lozère (FR814)	55.37	18.06
Maine-et-Loire (FR512)	12.81	78.06
Manche (FR252)	6.22	160.84
Marne (FR213)	31.59	31.66
Mayenne (FR513)	12.44	80.39
Meurthe-et-Moselle (FR411)	21.69	46.10
Meuse (FR412)	24.01	41.65
Morbihan (FR524)	18.38	54.39
Moselle (FR413)	19.6	51.02
Nièvre (FR262)	18.08	55.31

Name	m_{eff} 2009 (km²)	s_{eff} 2009 (number of meshes per 1 000 km²)
Nord (FR301)	7.78	128.48
Oise (FR222)	12.73	78.55
Orne (FR253)	11.52	86.84
Paris (FR101)	0.01	102 511.37
Pas-de-Calais (FR302)	7.23	138.22
Puy-de-Dôme (FR724)	16.84	59.38
Pyrénées-Atlantiques (FR615)	51.43	19.44
Pyrénées-Orientales (FR815)	148.46	6.74
Rhône (FR716)	8.89	112.54
Saône-et-Loire (FR263)	19.51	51.26
Sarthe (FR514)	13.48	74.18
Savoie (FR717)	55.59	17.99
Seine-et-Marne (FR102)	10.11	98.87
Seine-Maritime (FR232)	7.04	142.08
Seine-Saint-Denis (FR106)	0.18	5 525.09
Somme (FR223)	10.48	95.44
Tarn (FR627)	20.61	48.52
Tarn-et-Garonne (FR628)	17.67	56.59
Territoire de Belfort (FR434)	14.55	68.73
Val-de-Marne (FR107)	1.64	608.24
Val-d'Oise (FR108)	7.86	127.28
Var (FR825)	66.51	15.04
Vaucluse (FR826)	35.92	27.84
Vendée (FR515)	14.86	67.31
Vienne (FR534)	15.89	62.93
Vosges (FR414)	33.95	29.46
Yonne (FR264)	17.30	57.80
Yvelines (FR103)	6.74	148.30
(GR) Greece		
Anatoliki Makedonia, Thraki (GR11)	1 359.95	0.74
Attiki (GR30)	75.45	13.25
Dytiki Ellada (GR23)	195.39	5.12
Dytiki Makedonia (GR13)	143.65	6.96
Ionia Nisia (GR22)	35.72	28.00
Ipeiros (GR21)	138.81	7.20
Kentriki Makedonia (GR12)	192.74	5.19
Kriti (GR43)	147.25	6.79
Notio Aigaio (GR42)	82.80	12.08
Peloponnisos (GR25)	140.47	7.12
Sterea Ellada (GR24)	277.94	3.60

Name	m_{eff} 2009 (km²)	s_{eff} 2009 (number of meshes per 1 000 km²)
Thessalia (GR14)	247.16	4.05
Voreio Aigaio (GR41)	144.33	6.93
(HU) Hungary		
Bacs-Kiskun (HU331)	123.17	8.12
Baranya (HU231)	118.18	8.46
Bekes (HU332)	129.19	7.74
Borsod-Abauj-Zemplen (HU311)	137.13	7.29
Budapest (HU101)	3.37	296.92
Csongrad (HU333)	107.65	9.29
Fejer (HU211)	85.40	11.71
Gyor-Moson-Sopron (HU221)	88.40	11.31
Hajdu-Bihar (HU321)	123.40	8.10
Heves (HU312)	103.34	9.68
Jasz-Nagykun-Szolnok (HU322)	118.81	8.42
Komarom-Esztergom (HU212)	70.27	14.23
Nograd (HU313)	123.46	8.10
Pest (HU102)	94.84	10.54
Somogy (HU232)	134.47	7.44
Szabolcs-Szatmar-Bereg (HU323)	89.46	11.18
Tolna (HU233)	101.29	9.87
Vas (HU222)	44.48	22.48
Veszprem (HU213)	105.48	9.48
Zala (HU223)	60.90	16.42
(IE) Ireland		
Border (IE011)	176.03	5.68
Dublin (IE021)	25.87	38.65
Mid-East (IE022)	139.41	7.17
Midland (IE012)	126.04	7.93
Mid-West (IE023)	127.59	7.84
South-East (IRL) (IE024)	125.22	7.99
South-West (IRL) (IE025)	257.93	3.88
West (IE013)	187.81	5.32
(IT) Italy		
Abruzzo (ITF1)	98.34	10.17
Basilicata (ITF5)	105.40	9.49
Calabria (ITF6)	149.47	6.69
Campania (ITF3)	72.42	13.81
Emilia-Romagna (ITD5)	35.19	28.42
Friuli-Venezia Giulia (ITD4)	394.26	2.54
Lazio (ITE4)	85.52	11.69

Name	m_{eff} 2009 (km²)	s_{eff} 2009 (number of meshes per 1 000 km²)
Liguria (ITC3)	122.76	8.15
Lombardia (ITC4)	73.01	13.70
Marche (ITE3)	57.42	17.42
Molise (ITF2)	69.21	14.45
Piemonte (ITC1)	98.34	10.17
Provincia Autonoma Bolzano (ITD1)	115.04	8.69
Provincia Autonoma Trento (ITD2)	244.89	4.08
Puglia (ITF4)	36.61	27.31
Sardegna (ITG2)	291.64	3.43
Sicilia (ITG1)	118.16	8.46
Toscana (ITE1)	68.80	14.53
Umbria (ITE2)	107.35	9.32
Valle d'Aosta (ITC2)	133.98	7.46
Veneto (ITD3)	77.17	12.96
(LI) Liechtenstein		
	197.73	5.06
(LT) Lithuania		
Alytaus apskritis (LT001)	140.99	7.09
Kauno apskritis (LT002)	71.02	14.08
Klaipedos apskritis (LT003)	46.84	21.35
Marijampoles apskritis (LT004)	67.36	14.85
Panevezio apskritis (LT005)	78.02	12.82
Siauliu apskritis (LT006)	66.09	15.13
Taurages apskritis (LT007)	74.90	13.35
Telsiu apskritis (LT008)	64.36	15.54
Utenos apskritis (LT009)	55.34	18.07
Vilniaus apskritis (LT00A)	87.74	11.40
(LU) Luxembourg		
	7.40	135.17
(LV) Latvia		
Kurzeme (LV003)	130.11	7.69
Latgale (LV005)	111.79	8.95
Pieriga (LV007)	94.42	10.59
Riga (LV006)	8.62	116.01
Vidzeme (LV008)	106.05	9.43
Zemgale (LV009)	118.65	8.43
(MT) Malta		
	10.20	98.04
(NL) Netherlands		

Name	m_{eff} 2009 (km²)	s_{eff} 2009 (number of meshes per 1 000 km²)
Drenthe (NL13)	15.10	66.23
Flevoland (NL23)	30.28	33.03
Friesland (NL12)	18.02	55.51
Gelderland (NL22)	16.24	61.58
Groningen (NL11)	20.79	48.10
Limburg (NL) (NL42)	11.22	89.11
Noord-Brabant (NL41)	18.51	54.02
Noord-Holland (NL32)	14.14	70.72
Overijssel (NL21)	16.91	59.14
Utrecht (NL31)	8.28	120.77
Zeeland (NL34)	14.68	68.12
Zuid-Holland (NL33)	11.97	83.57
(NO) Norway		
Akershus (NO012)	246.29	4.06
Aust-Agder (NO041)	1 060.96	0.94
Buskerud (NO032)	835.40	1.20
Finnmark (NO073)	6 177.91	0.16
Hedmark (NO021)	1 042.37	0.96
Hordaland (NO051)	2 184.74	0.46
Møre og Romsdal (NO053)	506.58	1.97
Nordland (NO071)	3 051.95	0.33
Nord-Trøndelag (NO062)	3 529.11	0.28
Oppland (NO022)	933.38	1.07
Oslo (NO011)	443.80	2.25
Østfold (NO031)	108.21	9.24
Rogaland (NO043)	1 499.53	0.67
Sogn og Fjordane (NO052)	807.48	1.24
Sør-Trøndelag (NO061)	1852.85	0.54
Telemark (NO034)	607.08	1.65
Troms (NO072)	4 168.13	0.24
Vest-Agder (NO042)	974.78	1.03
Vestfold (NO033)	121.29	8.24
(PL) Poland		
Bialostocko-suwalski (PL341)	163.71	6.11
Bialskopodlaski (PL311)	52.37	19.09
Bielsko-bialski (PL225)	148.61	6.73
Bydgoski (PL611)	41.20	24.27
Centralny slaski (PL226)	36.44	27.44
Chelmsko-zamojski (PL312)	42.14	23.73
Ciechanowsko-plocki (PL121)	35.86	27.89
Czestochowski (PL224)	35.09	28.50

Name	m_{eff} 2009 (km²)	s_{eff} 2009 (number of meshes per 1 000 km²)
Elblaski (PL621)	40.78	24.52
Elcki (PL623)	95.21	10.50
Gdansk-Gdynia-Sopot (PL633)	9.28	107.81
Gdanski (PL632)	51.23	19.52
Gorzowski (PL431)	62.34	16.04
Jeleniogorsko-walbrzyski (PL511)	51.15	19.55
Kaliski (PL413)	34.40	29.07
Koninski (PL414)	39.57	25.27
Koszalinski (PL422)	61.64	16.22
Krakowsko-tarnowski (PL211)	21.47	46.58
Krosniensko-przemyski (PL322)	141.34	7.08
Legnicki (PL512)	30.68	32.59
Lodzki (PL111)	42.33	23.62
Lomzynski (PL342)	69.77	14.33
Lubelski (PL313)	36.75	27.21
Miasto Krakow (PL213)	7.51	133.07
Miasto Lodz (PL113)	10.50	95.26
Miasto Poznan (PL415)	11.20	89.32
Miasto Warszawa (PL127)	12.78	78.25
Miasto Wroclaw (PL514)	12.72	78.62
Nowosadecki (PL212)	139.83	7.15
Olsztynski (PL622)	60.05	16.65
Opolski (PL520)	35.46	28.20
Ostrolecko-siedlecki (PL122)	59.76	16.73
Pilski (PL411)	54.39	18.39
Piotrkowsko-skierniewicki (PL112)	35.69	28.02
Poznanski (PL412)	37.95	26.35
Radomski (PL124)	41.84	23.90
Rybnicko-jastrzebski (PL227)	14.75	67.80
Rzeszowsko-tarnobrzeski (PL321)	38.30	26.11
Slupski (PL631)	83.41	11.99
Swietokrzyski (PL330)	37.74	26.50
Szczecinski (PL421)	42.56	23.50
Torunsko-wloclawski (PL612)	41.45	24.13
Warszawski (PL126)	40.85	24.48
Wroclawski (PL513)	26.41	37.86
Zielonogorski (PL432)	47.58	21.02
(PT) Portugal		
Alentejo (PT18)	124.65	8.02

Name	m_{eff} 2009 (km²)	s_{eff} 2009 (number of meshes per 1 000 km²)
Algarve (PT15)	100.7	9.93
Centro (P) (PT16)	83.05	12.04
Lisboa (PT17)	27.61	36.22
Norte (PT18)	74.00	13.51
Região Autonoma da Madeira (PT30)	687.86	1.45
Região Autonoma dos Açores (PT20)	445.93	2.24
(RO) Romania		
Alba (RO071)	1 944.55	0.51
Arad (RO051)	1 624.11	0.62
Arges (RO031)	1 121.65	0.89
Bacau (RO011)	2114.80	0.47
Bihor (RO061)	1 974.23	0.51
Bistrita-Nasaud (RO062)	2 336.34	0.43
Botosani (RO012)	558.13	1.79
Braila (RO021)	593.38	1.69
Brasov (RO072)	1 830.17	0.55
Bucuresti (RO081)	3.36	297.92
Buzau (RO022)	2 955.18	0.34
Calarasi (RO032)	480.43	2.08
Caras-Severin (RO052)	2 833.50	0.35
Cluj (RO063)	2 680.75	0.37
Constanta (RO023)	825.73	1.21
Covasna (RO073)	3 281.41	0.30
Dambovita (RO033)	734.48	1.36
Dolj (RO041)	1 457.93	0.69
Galati (RO024)	1 551.81	0.64
Giurgiu (RO034)	526.77	1.90
Gorj (RO042)	1 795.45	0.56
Harghita (RO074)	2 214.44	0.45
Hunedoara (RO053)	2 316.38	0.43
Ialomita (RO035)	609.95	1.64
Iasi (RO013)	808.43	1.24
Ilfov (RO082)	208.20	4.80
Maramures (RO064)	2 641.91	0.38
Mehedinti (RO043)	1 919.40	0.52
Mures (RO075)	1 734.56	0.58
Neamt (RO014)	1 326.64	0.75
Olt (RO044)	972.88	1.03
Prahova (RO036)	1 279.18	0.78
Salaj (RO066)	1 657.31	0.60
Satu Mare (RO065)	809.53	1.24
Sibiu (RO076)	2 460.40	0.41
Suceava (RO015)	1 703.43	0.59

Name	m_{eff} 2009 (km²)	s_{eff} 2009 (number of meshes per 1 000 km²)
Teleorman (RO037)	971.89	1.03
Timis (RO054)	848.01	1.18
Tulcea (RO025)	1 176.44	0.85
Valcea (RO045)	1 133.95	0.88
Vaslui (RO016)	1 617.16	0.62
Vrancea (RO026)	4 375.96	0.23
(SE) Sweden		
Blekinge län (SE041)	73.10	13.68
Dalarnas län (SE062)	845.31	1.18
Gävleborgs län (SE063)	559.80	1.79
Gotlands län (SE094)	168.81	5.92
Hallands län (SE0A1)	67.72	14.77
Jämtlands län (SE072)	3 625.86	0.28
Jönköpings län (SE091)	146.05	6.85
Kalmar län (SE093)	184.76	5.41
Kronobergs län (SE092)	136.44	7.33
Norrbottens län (SE082)	3 611.57	0.28
Örebro län (SE024)	189.64	5.27
Östergötlands län (SE023)	147.17	6.79
Skåne län (SE044)	71.91	13.91
Södermanlands län (SE022)	100.90	9.91
Stockholms län (SE010)	89.93	11.12
Uppsala län (SE021)	159.94	6.25
Värmlands län (SE061)	380.08	2.63
Västerbottens län (SE081)	1 956.78	0.51
Västernorrlands län (SE071)	560.84	1.78
Västmanlands län (SE025)	174.39	5.73
Västra Götalands län (SE0A2)	114.82	8.71
(SI) Slovenia		
Gorenjska (SI022)	294.21	3.40
Goriska (SI023)	199.51	5.01
Jugovzhodna Slovenija (SI017)	90.54	11.04
Koroska (SI013)	73.06	13.69
Notranjsko-kraska (SI018)	261.73	3.82
Obalno-kraska (SI024)	42.20	23.70
Osrednjeslovenska (SI021)	39.72	25.18
Podravska (SI012)	14.53	68.84
Pomurska (SI011)	16.11	62.09

Name	m_{eff} 2009 (km²)	s_{eff} 2009 (number of meshes per 1 000 km²)
Saviinjska (SI014)	34.64	28.87
Spodnejpodsvska (SI016)	34.29	29.16
Zasavska (SI015)	23.11	43.27
(SK) Slovakia		
Banskobystricky kraj (SK032)	234.08	4.27
Bratislavsky kraj (SK010)	95.53	10.47
Kosicky kraj (SK042)	168.26	5.94
Nitriansky kraj (SK023)	63.83	15.67
Presovsky kraj (SK041)	305.83	3.27
Trenciansky kraj (SK022)	206.66	4.84
Trnavsky kraj (SK021)	52.97	18.88
Zilinsky kraj (SK031)	365.58	2.74
(SM) San Marino		
	22.75	43.96
(UK) United Kingdom		
Bedfordshire and Hertfordshire (UKH2)	44.22	22.61
Berkshire, Buckinghamshire and Oxfordshire (UKJ1)	46.75	21.39
Cheshire (UKD2)	25.43	39.32
Cornwall and Isles of Scilly (UKK3)	80.57	12.41
Cumbria (UKD1)	289.85	3.45
Derbyshire and Nottinghamshire (UKF1)	50.37	19.85
Devon (UKK4)	134.03	7.46
Dorset and Somerset (UKK2)	77.63	12.88
East Anglia (UKH1)	64.16	15.59
East Riding and North Lincolnshire (UKE1)	65.75	15.21
East Wales (UKL2)	212.23	4.71
Eastern Scotland (UKM2)	482.13	2.07
Essex (UKH3)	45.17	22.14

Name	m_{eff} 2009 (km²)	s_{eff} 2009 (number of meshes per 1 000 km²)
Gloucestershire, Wiltshire and North Somerset (UKK1)	61.04	16.38
Greater Manchester (UKD3)	10.08	99.21
Hampshire and Isle of Wight (UKJ3)	54.98	18.19
Herefordshire, Worcestershire and Warwickshire (UKG1)	54.58	18.32
Highlands and Islands (UKM4)	747.05	1.34
Inner London (UKI1)	0.03	33 743.86
Kent (UKJ4)	48.13	20.78
Lancashire (UKD4)	192.87	5.18
Leicestershire, Rutland and Northamptonshire (UKF2)	77.25	12.94
Lincolnshire (UKF3)	74.55	13.41
Merseyside (UKD5)	4.94	202.24
North Eastern Scotland (UKM1)	483.15	2.07
North Yorkshire (UKE2)	257.45	3.88
Northern Ireland (UKN0)	107.50	9.30
Northumberland and Tyne and Wear (UKC2)	406.49	2.46
Outer London (UKI2)	3.62	276.34
Shropshire and Staffordshire (UKG2)	64.81	15.43
South Western Scotland (UKM3)	245.35	4.08
South Yorkshire (UKE3)	44.39	22.53
Surrey, East and West Sussex (UKJ2)	38.81	25.77
Tees Valley and Durham (UKC1)	117.44	8.51
West Midlands (UKG3)	2.60	385.35
West Wales and The Valleys (UKL1)	153.14	6.53
West Yorkshire (UKE4)	33.71	29.66

Annex 2 Cross-boundary connections (CBC) procedure

The boundaries of reporting units often do not coincide with the location of physical fragmenting elements in the landscape. Therefore, patches crossing the boundaries of reporting units need to be attributed to the reporting units in some suitable, unambiguous way. This requirement causes a problem in calculating landscape fragmentation metrics, because methods for these metrics often cut habitat patches off at the boundaries of the reporting unit being analysed ('cutting-out procedure'). The cutting-out (CUT) procedure cuts patches at the edge of a given planning unit (like a cookie cutter), and ignores contiguous parts of patches located outside the unit boundary. If these patch parts are large, this approach can generate considerable negative bias in the results, constituting the so-called boundary problem (Moser et al., 2007). This is the case with the original method for calculating the effective mesh size landscape metric (Jaeger, 2000). However, recent advances in landscape metric theory have led to a modified effective mesh size calculation that accounts for cross-boundary connections (Moser et al., 2007). An alternative implementation is the cross-boundary connection (CBC) procedure, which accounts for connected unfragmented areas that extend beyond the boundaries of a given planning unit for which the effective mesh size is being calculated. Therefore, this study applied the CBC procedure. The CBC effective mesh size calculation for a given reporting unit *j* is calculated using the following formula (Moser et al., 2007):

$$m_{\mathrm{eff}}^{\mathrm{CBC}}(j) = \frac{1}{A_{tj}} \sum_{i=1}^{n} A_{ij} \cdot A_{ij}^{\mathrm{cmpl}}$$

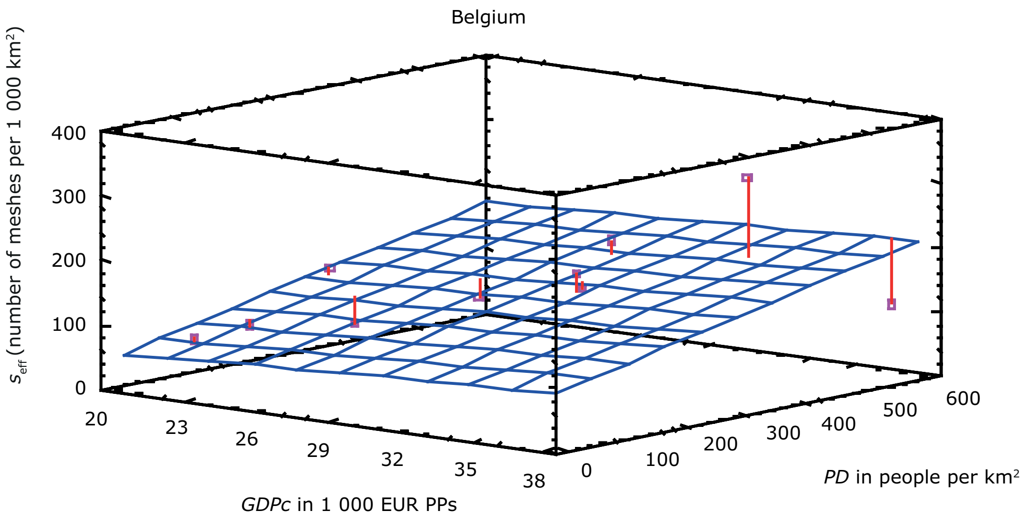
where n is the number of patches intersecting reporting unit j, A_{tj} is the total area of reporting unit j, A_{ij} is the area of patch i inside of planning unit j, and A_{ij}^{cmpl} is the complete area of patch i including the area outside the boundaries of planning unit j.

Annex 3 Statistical methods

To examine how strongly socioeconomic and geophysical variables are related to fragmentation levels, we used generalised linear models (GLM), as illustrated in Figure A3.1. A global linear regression model was developed containing all the geophysical and socioeconomic variables. Model selection was done by successively adding variables for which we had a working hypothesis. All possible combinations of the explanatory variables were examined.

To rank our competing models, we used the Akaike information criterion (AIC). The AIC is based on the number of observations, the residual sum of squares (also called error sum of squares, SSE), and the number of estimable variables in the model (Burnham and Anderson, 2002). The AIC method identifies the most parsimonious explanation among the competing models without over-fitting them. To determine the relative importance of each one of the predictor variables in the most parsimonious model we used commonality analysis. Commonality analysis is a form of variance partitioning and is used to determine the relative importance of predictor variables. It partitions the explained variance (as measured by R^2 from the GLMs) into (a) the fractions that are uniquely explained by each predictor variable (or a particular predictor subset) and (b) the fractions that are commonly explained by all possible combinations of predictors (or predictor subsets). This approach facilitates the interpretation of the results by quantifying how much explanatory power can be attributed to each predictor (Reichwein Zientek and Thompson, 2006; Chevan and Sutherland, 1991). Finally we used the most parsimonious GLM model in each group of regions to develop a map of observed versus predicted fragmentation levels.

Figure A3.1 Illustration of the statistical analysis using multiple linear regression



Note: This simple example uses the data of the NUTS-X regions from Belgium (FG-B2). The effective mesh density (s_{eff}) is shown as the response variable as a function of two predictor variables: population density (*PD*, between 64 and 600 people per km²) and gross domestic product per capita (*GDPc*, between 20 500 and 37 000 euros *PPs*). The gridded plane shows the predicted values for the effective mesh density for each combination of *PD* and *GDPc*. The differences between the observed values of s_{eff} (shown as small squares) and the predicted values are shown as perpendicular lines and are called residuals. In this example, the predicted level of fragmentation increases with higher population densities and with higher gross domestic product per capita, and the variation in population density has a higher influence than the variation in *GDPc*.

Source: EEA/FOEN, 2011.

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