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Regional Degradation Index (RDI) for Europe: A physically based model for estimating long-term average rates of soil erosion by water, at regional scales

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Regional Degradation Index (RDI) for Europe:
A physically based model for estimating long-term average rates of soil erosion by water, at regional scales

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Summary[1].

This methodology is for estimating water erosion risk for large areas. The estimates are based on a 1-dimensional hydrological balance and a physically based sediment transport model. Estimates of risk associated with a given storm amount are integrated over the frequency distribution of daily rainfalls to provide a properly weighted estimate of the average annual risk. Soil factors are estimated from textural classes using qualitative pedo-transfer functions. Climatic data is taken from interpolated gridded data. Topographic data is taken from global or local DEMs. The estimates are for sediment delivery to stream channels. The method has been applied to provide a published map for most of Europe at 1 km resolution, and has been applied to smaller areas at resolutions of 250m and finer. Pan-European data have been taken primarily from the MARS climate data base (50km), EROS SRTM DEMs (90m) and the European Soils Data Base (1 km).

Current Pan European erosion estimates are displayed below. The PESERA modelling strategy is detailed on PESERA website:

http://pesera.jrc.it

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[1] **Main references**:

de Ploey, J., M.J. Kirkby & F. Ahnert, 1991. Hillslope erosion by rainstorms - a magnitude-frequency analysis. Earth Surface Processes & Landforms 16, 399-409.

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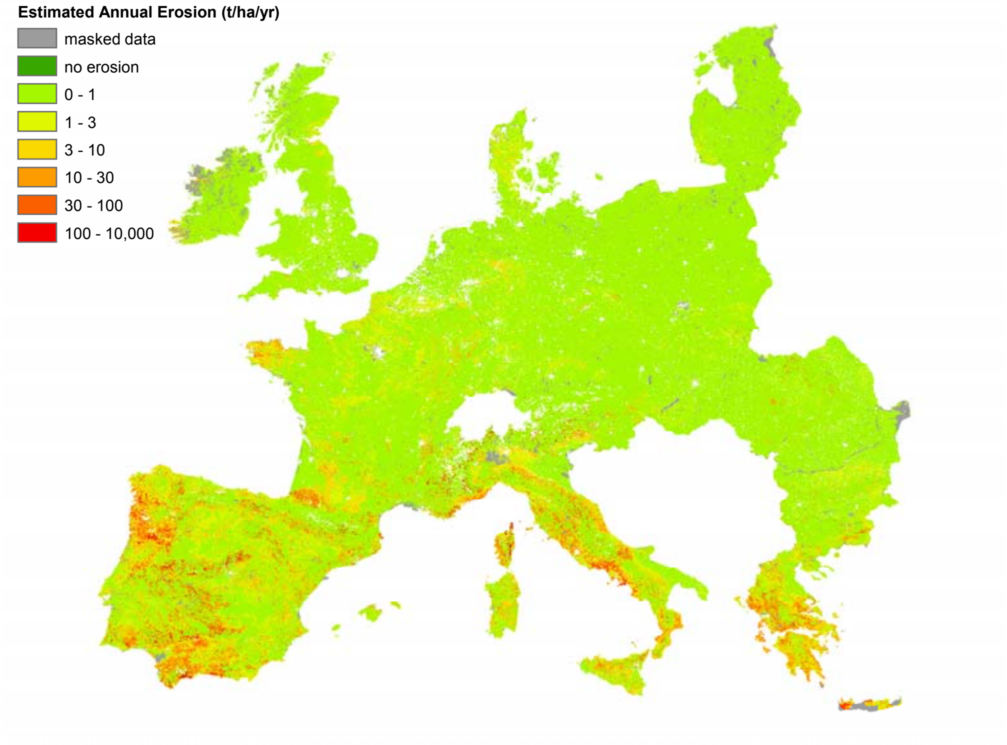
Map of Estimated Erosion Risk for Europe at a 1-km Resolution

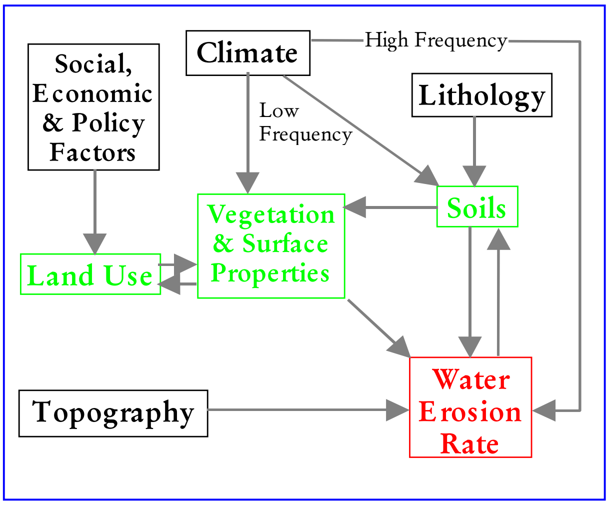


Introduction

Erosion by running water has been identified as the most severe hazard threatening the protection of soil in Europe. By removing the most fertile topsoil, erosion reduces soil productivity and may, where soils are shallow, lead to an irreversible loss of natural farmland. Severe erosion is commonly associated with the development of temporary or permanently eroded channels or gullies that can fragment farmland. The soil and runoff removed from the land in a large storm accumulates below the eroded areas, in severe cases blocking roadways or channels and inundating buildings. Erosion rate is very sensitive to both climate and land use, as well as to detailed conservation practice at farm level. In a period of rapid changes in both climate and land use, due to global change, revised agricultural policies and international markets, it is valuable to be able to assess the state of soil erosion at a European level, using an objective methodology which allows the assessment to be repeated as conditions change, or to explore the broad scale implications of prospective global or Europe-wide changes. This provides an estimate of the overall costs attributable to erosion under present and changed conditions, and objectively suggests areas for more detailed study and possible remedial action.

National, European and International agencies need objective information at scales of 1:250,000 to 1:1,000,000 to compare levels of environmental risks, as an aid to economic planning and policy development. Despite the increasingly effective use of Remote Sensing, many risk factors are not directly accessible, particularly at this scale. At present, much more can be achieved by combining physically based models with remotely sensed land cover, digital elevation models, gridded climate data and databases of fixed soil and other characteristics. The RDI/PESERA model presented here is based on preliminary theoretical work by de Ploey et al (1991) and Kirkby and

Cox (1995), developed through a series of EU projects (MEDALUS 1994-97, MoDeM 1998-99, PESERA 2000-04 and DESERTLINKS 2001-05) - in co-operation with many partners. A preliminary erosion risk map of France was prepared, in collaboration with JRC and INRA (Institute Nationale pour Recherches Agronomiques), Orléans, for comparison with CORINE methods (Briggs and Giordiano, 1992), and these methods are continuing to be refined, improved and extended to salinity, off-site effects and nutrients.



The physical model is based on a 1-dimensional SVAT (Soil-Vegetation-Atmosphere Transfer) type scheme for surface hydrology, coupled where appropriate to a dynamic model for generic vegetation growth and/or remotely sensed land use data. Water Erosion is directly controlled by:

Climate - through the distribution of storm events;

Vegetation - via crown cover, providing protection from rainsplash impact and via root mat strength;

Soil properties - texture, organic matter and structure influence both water storage and resistance to sediment detachment and transport (erodibility);

Topography – through hillslope length (representing the collecting area for overland flow) and through gradient (as the driver for sediment traction).

A number of these factors act through agricultural land use, which is strongly influenced by economic and social factors.

There are several possible methodologies for creating a regional erosion map. Some of these are based on the collection of distributed field observations, others on an assessment of factors, and combinations of factors, which influence erosion rates, and others primarily on a modelling approach. All of these methods require calibration and validation, although the type of validation needed is different for each category. There are also differences in the extent to which the assessment methods identify past erosion and an already degraded soil resource, as opposed to risks of future erosion, under either present climate and land use, or under scenarios of global change.

Distributed point data

One important form of erosion assessment is from direct field observations of erosion features and soil profile truncation. Erosion features consist of rills and gullies, some of these ephemeral, and associated deposition in swales and small valleys. Soil profiles may show local loss of upper horizons, or burial by deposition from up-slope. Deposited material may provide dateable material that can indicate when erosion occurred, but much of this evidence is cumulative over the period since cultivation began, or in some cases over the whole of the Holocene. Data may be collected from regional experts in soils or soil erosion. They may also be collated from field or remote (air photo) surveys of erosion features. Higher satellite resolution (e.g. IKONOS) may, in the near future, also allow this method to be applied from space platforms. Some quantitative data are also available from erosion plot sites.

These methods require validation to standardise differences in the intensity of study of different areas and in the clarity of suitable features on different soil types. There are also differences in methods and traditions between scientists in different areas of Europe. On their own these methods cannot provide a complete picture except for small sample areas, and require the use of other methods to interpolate between areas.

The main advantage of distributed observations of erosion is that data are unambiguous where they exist, and give a good indication of the current state of degradation of the soil resource, and other methods lack this certainty. The main disadvantage of these methods is that they provide little or no information about when erosion occurred, unless there are supporting data on this point. Many areas of the Mediterranean are thought to have suffered anthropogenic acceleration of erosion since early classical times, and many hills are now denuded of their former natural soil cover. Although of great historical interest, this has little bearing on current or prospective erosion hazards.

Factor or Indicator Mapping

Since many of the processes and factors which influence the rate of erosion are well known, as outlined above, it is possible to rank individual factors for susceptibility to erosion, providing a series of erosion indicators. For example, climatic indices may be based on the frequency of high intensity precipitation, and on the extent of aridity or rainfall seasonality. Soil indicators may reflect the tendency to crusting and the experimental erodibility of soil particles or aggregates. Similar rank indicators may be developed for parent materials, topographic gradient and other factors. Clearly a high susceptibility for all factors indicates a high erosion risk, and a low susceptibility for all factors indicates a low erosion risk.

Individual indicators may be mapped separately, but it is more problematic to combine the factors into a single scale, by adding or multiplying suitably weighted indicators for each individual factor. There are difficulties both about the individual weightings and about the assumed linearity and statistical independence of the separate factors. The method should therefore be most effective for identifying the extremes of high and low erosion, but less satisfactory in identifying the gradation between the extremes.

Despite these theoretical limitations, factor or indicator mapping has the considerable advantage that it can be widely applied using data which is available in Europe-wide GIS for topography and soils at 1 km resolution, and for climate at 50 km resolution. Kosmas *et al* (1999) provides one example of this approach, applied at a regional scale to areas in Greece, Italy and Portugal. Factor mapping can also take account of a wider range of factors, as illustrated by the Environmental Sensitivity Index (ESI) within DIS4ME, which also considers sensitivity to salinisation and other desertification hazards.

Process modelling

There is a continuous spectrum between mapping based on ranked indicators and process models with a more explicit physical or empirical basis. Nevertheless it is fruitful to consider, as a third approach towards Europe-wide soil erosion assessment, the application of a process model. Although, at first sight, this approach appears to be the most generally applicable, there are major problems of validation, and in particular in relating coarse scale forecasts to available erosion rate data, much of which is for small erosion plots. Many of the most successful process models require more detailed distributed parameter and rainfall intensity data than are currently available at pan-European scales, so that they cannot be applied without radical simplification. One important aspect of this problem is the need to develop a model that can be used for validation at fine scales, and for Europe-wide forecasting at a coarse scale, so that cross-scale reconciliation must be as explicit as possible. Nevertheless this approach has the potential to provide a rational physical basis to combine factors which can be derived from coarse scale GIS, and overcome the difficulties about weighting and inter-correlation which are encountered in purely factor based assessments.

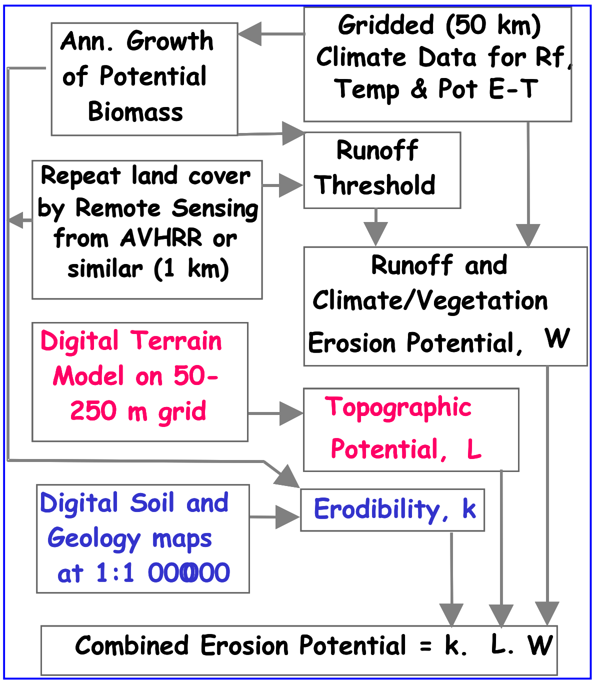
Process models have the potential to respond explicitly and rationally to changes in climate or land use, and so have great promise for developing scenarios of change, and what-if analyses of policy or economic options. Set against this advantage, process models generally make no assessment of degradation up to the present time, and can only incorporate the impact of past erosion where this is recorded in other data, such as soils data bases. Models also generally simplify the set of processes operating, so that they may not be appropriate under particular local circumstances. Although the USLE has been the most widely applied model in Europe (e.g. van der Knijff *et al*, 2000), it is now widely considered to be conceptually flawed, and other models are now emerging, based on runoff thresholds (e.g. Kirkby *at al*, 2000) or the MI(Minimum Information Requirement) approach (Brazier *et al*, 2001) applied to the more complex USDA WEPP model (Nearing *et al*, 1989).

The application of a process model has been preferred here for three main reasons:

- It applies the same objective criteria to all areas, and so can be applied throughout Europe, subject to the availability of suitable generic data
- It provides a quantitative estimate of erosion rate that can be compared with long term averages for tolerable erosion
- The methodology can be re-applied with equal consistency with improved current data, and for scenarios of changed climate and land use

Scientific Rationale for Estimating Erosion Risk

The PESERA model (Pan–European Soil Erosion Risk Assessment) is a physically based and spatial distributed model developed in quantifying soil erosion of Environmentally Sensitive Areas (ESAs) relevant to a regional or European scale and defining soil conservation strategies. The current version of model was developed during the execution of the PESERA project (Contract QLK5-CT-1999-01323) funded by the European Commission, Research Directorates General, DG VI (Quality of Life and Management of Living Resources), and was also based on previous funded and un-funded research



(Kirkby and Neale, 1987; de Ploey et al, 1991; Kirkby and Cox, 1995; Kirkby et al, 2000).

The PESERA model combines the effect of topography, climate and soil into a single integrated forecast of runoff and soil erosion. Data for each of these three factors have been extracted from existing sources and combined in a physically based model to make rational forecasts of soil erosion. The model is built in three conceptual stages, explained more fully below:

1. A storage threshold model to convert daily rainfalls to daily total overland flow runoff
2. A power law to estimate sediment transport from runoff discharge and gradient, and interpret sediment transport at the base of the hillside as average erosion loss.
3. Integration of daily rates over the frequency distribution of daily rainfalls to estimate long-term average erosion rates.

Storage Model

PESERA uses the simplest possible storage, or bucket model to convert daily rainfall to daily overland flow runoff. Runoff is estimated as Rainfall minus a threshold storage. The threshold depends on a number of factors related to the soil, vegetation cover, tillage and soil moisture status. The most important soil factors are texture, soil depth (if shallow) and soil organic matter which determine the threshold storage beneath the vegetation covered fraction of the surface. Where not protected by vegetation, the susceptibility of the soil to crusting and the duration of crusting conditions generally determines a lower threshold. The final threshold is a weighted average from vegetated and bare fractions of the surface. Corrections are made for the soil water deficit, which may reduce the threshold where close to saturation.

The model is normally linked to a simple biomass model to allow crops or natural vegetation to respond to seasonal variations in available moisture, and allows some subsurface drainage of soil moisture. Alternatively the model can make use of vegetation cover derived from remotely sensed data. This has the advantage of taking into account factors not included in the model, such as grazing intensity and fire, but does not provide scenario capability. All the factors are assessed on a monthly basis so that the threshold may vary markedly through the year. Calculations are modified appropriately where there is frozen ground or snow cover.

Power law sediment Model

Daily total runoff is linearly scaled up to discharge for each point in an area, and daily sediment transport is estimated as:

$$\textit{Sediment Transport} = \textit{Erodibility} \times (\textit{Runoff} \times \textit{Distance from divide})^2 \times \textit{Gradient}$$

Erodibility is primarily associated with the soil texture, but is reduced to allow for a full or partial vegetation cover. Gradient is derived from topographic sources, but will not be required for estimating the whole-slope erosion loss.

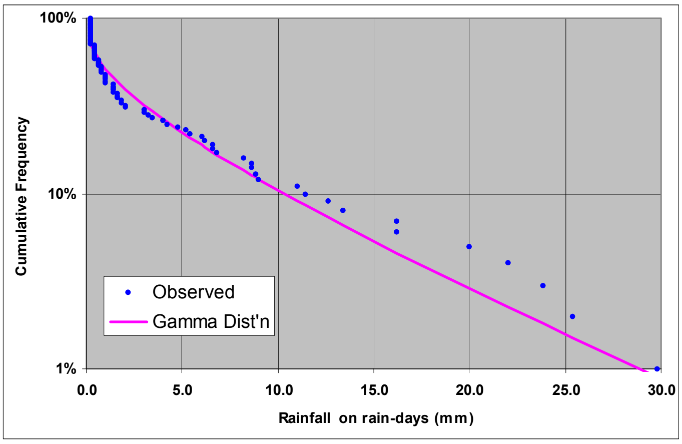
If sediment transport is estimated at the slope base, then this expression can be re-written for sediment yield (*Total sediment transport ÷ Total slope length*) as:

$$\textit{Sediment Yield} = \textit{Modified Erodibility} \times \textit{Runoff}^2 \times \textit{Relief}$$

where the modified erodibility includes a small correction factor for the ratio of slope-base local gradient to mean slope gradient (which is implicit in the term *Relief* = *Total slope Length* × *Mean gradient*). This allows the use of coarse resolution DEMs which can estimate Relief as the variability of local elevation, without the need to estimate local gradients directly, which is advantageous where DEM point spacing may be of the same order as total slope length.

Estimating long-term average erosion rates

Daily rainfall data is used because of its wide availability. The forecasting model can be used with a time series of daily rainfalls, but maps derived on this basis show a strong signal associated with the historic locations of the largest storms. Instead the map provides a weighted average of annual erosion, summed over the frequency distribution of daily rainfalls for each month. This frequency distribution is derived from an analysis of historic time series for each month separately, using the number of rain days, mean rain per rain day and its standard deviation to fit a Gamma distribution which provides an excellent fit (see graph) to long data series. The daily runoff and daily erosion for each possible rainfall is weighted by its frequency in this distribution to estimate the long-term averages for each month, and summed for annual totals.



Integrated model

The calculations described above are performed independently for each cell within a 1 km grid across Europe. The one-cell model is available as an Excel spreadsheet with Visual Basic macros through the PESERA web site (http://pesera.jrc.it) and can be used to estimate runoff and erosion rates for a single point, and to show the effect of changes in land use or climate on expected rates. The main model repeats these estimates for each 1×1 km cell within an area, combining data in ARC-Grid format with FORTRAN code, and creating output maps which can be examined or interrogated in ARC-VIEW. Advice on preparation of databases and running the grid model can also be obtained through the web site, and a prototype system allows the model to be run remotely for small areas (up to 100 × 100 km) over the net .

Calibration and Validation

Because there are only a limited number (50-100) of acceptable measures of erosion rates across Europe, and these differ significantly in methodology and scale, a pan-European calibration of erosion rates is not practicable. The overall reliability of the model is based on a internal, intermediate and external calibration

Internal validation is based on a qualitative and quantitative assessment of the physical representation of processes in the model. This includes our accumulated understanding of process mechanics and their incorporation in the model in a sufficiently simplified form and judgements on which processes should be included.

Intermediate validation is based on comparison with spatial distributions which are forecast within the model as intermediate products. The most important of these distributions is of vegetation cover and abundance, which are derived within the model by combining land use data with a growth model, and can be independently corroborated from remote sensing interpretations. Comparison can also be made with seasonal runoff patterns.

External calibration is based on comparison with erosion plot (40 m^2), small catchment (0.01-1 km^2) and reservoir (1-100 km^2) data (Cerdan, 2003; Tsara *et al*, in press). These data have been used primarily to modify the pedo-transfer functions, particularly for soil erodibility. Comparative data are considered too sparse to allow a formal independent validation test.

Data: current sources and limitations

Four main datasets are required to run the model, to provide essential climate, soils, land cover and topographic data . These have been made available within the PESERA project from a mixture of public and restricted sources .

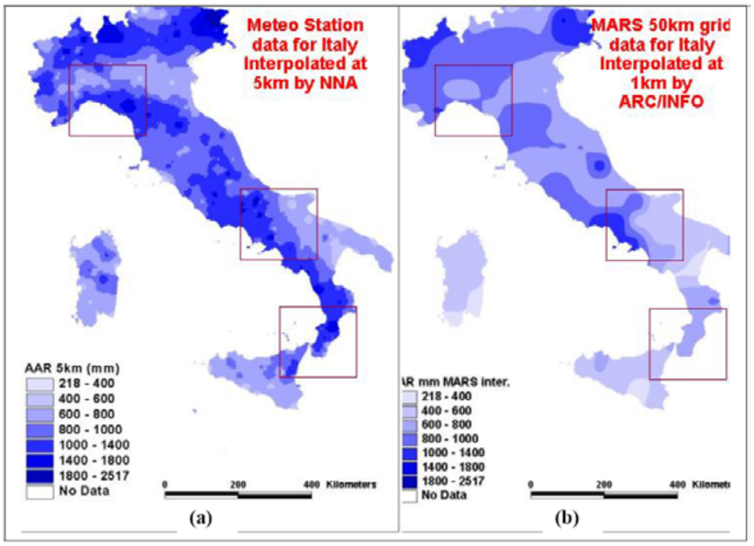
Climate data

The MARS database, assembled by JRC-Ispra , provides daily time series of rainfall, temperature and potential evapotranspiration, interpolated to a 30 second (approximately 50 km) grid for Europe . These data have been analysed to provide the following monthly data layers for the model:

Rainfall: Number of rain days, mean rain per rain day and its standard deviation to provide the distribution of daily rainfalls.

Temperature: Mean, mean maximum and mean minimum required only in areas where there is soil freezing or snowfall.

Potential evapotranspiration to estimate actual evapotranspiration, plant production and water balance.



(a) (b)

This is judged by comparing the inset map of mean annual rainfall based on these data with published national maps derived from individual station data. As another example, Brittany is shown with an unexpectedly high rainfall. An improved climate database, particularly for rainfall, has the potential to significantly improve the erosion forecasts of the PESERA/RDI model.

Soils data

The European Soils database, prepared by JRC-Ispra and INRA-Orleans, has been used to provide a consistent level of soils data at 1 km resolution across Europe. In conjunction with a series of pedo-transfer functions based on work by INRA-Orleans, the database has been used to provide three data layers for the model:

- *Soil erodibility* which converts runoff to erosion rates using the power law for sediment transport.
- *Readily available Soil Water Capacity* which provides the maximum storage capacity of the soil before runoff occurs under vegetation.
- *Crustability* which sets the lower limit of storage capacity for a crusted soil in unvegetated areas.

Soil water capacity is also used to define the drainage characteristics of the soil. Although there is scope to produce dedicated maps for these soil properties, and pedo-transfer functions over-simplify the complexities of soil dynamic properties, it is unrealistic to expect major improvements in these variables in the near future. However, some improvement can be made where more detailed soil maps are available for areas of particular interest.

Land cover

Land cover may be derived from remote sensing, or from land use maps in combination with a vegetation growth model. Remote sensing methods use data from AVHRR or LANDSAT imagery. AVHRR provides a 20-year monthly time series at 8 km resolution, and 15 years at 1 km resolution, but is limited by cloud cover in northern Europe. LANDSAT has the potential to provide 30m resolution, but has not been used. All remote sensing methods have the advantage of providing a measure of cover which includes the effects of all factors, but has no direct potential for scenario analysis, and land use surveys have been the primary data source for the erosion map. Land use is based on CORINE land cover at 250 m resolution for 1989. CORINE 2000 will shortly become available to update the estimates. Land use data is combined with cereal planting dates, generalised from EUROSTAT, to provide the parameters for a crop or natural vegetation growth model.

Topography

A 30 second (1 km) DEM has been available from EROS for some years, and has been the basis for work on PESERA, and for the erosion map. The critical parameter for the model is local relief, which has been estimated from DEMs as the standard deviation of elevation within a circle of 3 km diameter around each cell. Comparison with DEMs at improved resolution (down to 30 m) has shown that this measure is insensitive to DEM resolution, and can therefore be used reliably with the best DEMs available for each area. Recently the SRTM 3 second (90m) DEM has been released for Europe, and this is being used to refine the data layer for local relief.

The future: data improvements, scenarios of change and extensions to the model

The greatest potential for improvement in these erosion estimates lies in better climate data, and this is potentially available in national records, although not free of charge. Soils data could also be improved in principle, although this is unlikely to occur in the near future. Land cover requires frequent updating, because changes in land use have a major impact on erosion rates. There is the potential to do this through the analysis of remotely sensed images and through crop models with changed climate data or scenarios. For scenarios of alternative erosion futures, improvements in GCMs and economic forecasts also offer a potential that is still far from full realisation.

Hadley Centre and other climate scenarios, on their own, indicate some increases in soil erosion around the Mediterranean, particularly for the winter months. However economic and CO_2 scenarios seem to indicate some increases in European crop yields. If these increases are taken up by reductions on arable area that reduce dependence on marginal land, then European erosion rates might decline. A more global view, however, suggests that crop yields will decline worldwide, and therefore increase pressure on European arable land. According to this scenario, economic and climatic trends may both contribute to increases in erosion.

Salinity

Although the processes influencing salinity are not as well understood as for soil erosion, a factor-based indicator of salinity risk has been developed on the same scale as the PESERA/RDI erosion estimate, and using many of the same data layers. In developing this indicator, parent material has been used rather than soil characteristics, in order to try to clearly distinguish cause and effect, and so minimise circularity in the reasoning. Salinisation may be primary, in which saline or sodic soils develop under natural vegetation, but the greatest risk in the context of desertification is secondary salinity, which develops in irrigated areas where the water given to crops is insufficient to leach out accumulating salts.

The most important factors that promote salinity are the presence of saline parent materials and a high groundwater table. Many areas around the Mediterranean have undergone tectonic uplift during the Tertiary and Quaternary periods, as a result of the collision between African and European plates that has created the Alps, Pyrenees, Carpathians and Betic mountain ranges. As a result there are many land areas with Tertiary or later marine sediments at the surface, and these are geologically young enough to still retain much of their marine salt content, with lowest leaching losses during dry climatic phases. Older deposits have lost much of the salt, and soils on them are at lower risk of salinisation, and generally suffer less from poor groundwater quality. High groundwater tables are associated with areas of low internal relief, with poor lateral drainage towards the sea or large perennial rivers. These three factors have been combined to estimate a qualitative salinity risk, in the form:

SALINITY = (0.1 + PM) * FLUX / (10 + STDEVEL)

Where PM (Parent material) =1 for Tertiary sediments, 0 otherwise

FLUX = Net acc'd upward or downward Rainfall/ Evap flux, whichever is less

STDEVEL = Relief, estimated as standard deviation of local elevations.

The constants in the formula are chosen to retain reasonable ranges of the combined risk for extreme parameter values. In calculating risks for secondary salinisation, it is assumed that the flux term is calculated using a 'rainfall' that includes enough irrigation water to supply the potential evapotranspiration need of the crop.

Additional factors which might also be considered for inclusion include:

Factor	**Sign**	**Relevance**
Distance from sea	-	In-blowing of salt spray over c. 50 km
Electrical conductivity (μS) or Total dissolved Solids (mg l^{-1}) of Soil and irrigation water	+	Quality of water available for irrigation, or drawn up naturally from shallow groundwater table

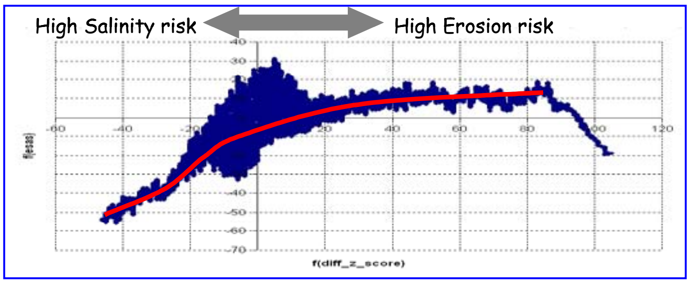
% clay content of soils	+	Sodium combines with clays to create severely sodic soils
[Na/(Na+Ca)] for soil or parent material	+	High Sodium: Calcium ratio also promotes the development of sodic soils
Age of youngest marine sedimentary deposits	-	Older sediments have generally lost more of their original marine salt content.

Off-site effects

Where areas of high erosion have silt or fine sand soils, much of the eroded material is re-deposited immediately downstream of eroded fields, creating ‘muddy floods’ which can severely damage buildings and disrupt roadways and villages. The direct loss of soil brings long-term costs, through increased fertiliser requirements and, in extreme cases, loss of cultivable land. However, the off-site effects are, in many cases, the most expensive and immediate impacts of erosion, and may provide an early warning of severe local erosion problems.

To assess these local off-site impacts, the PESERA/RDI model has been used to estimate the erosion associated with the 100-year event, extrapolated from the distribution of daily rainfalls. The eroded material is routed to neighbouring grid cells, with a sediment delivery ratio which decreases with local relief and with the grain size of the eroded soil. As sediment is routed from cell to cell, deposition in each is calculated from the reduction in material transported. Thus off-site effects are most severe when steep sand/silt soils are adjacent to flatter land.

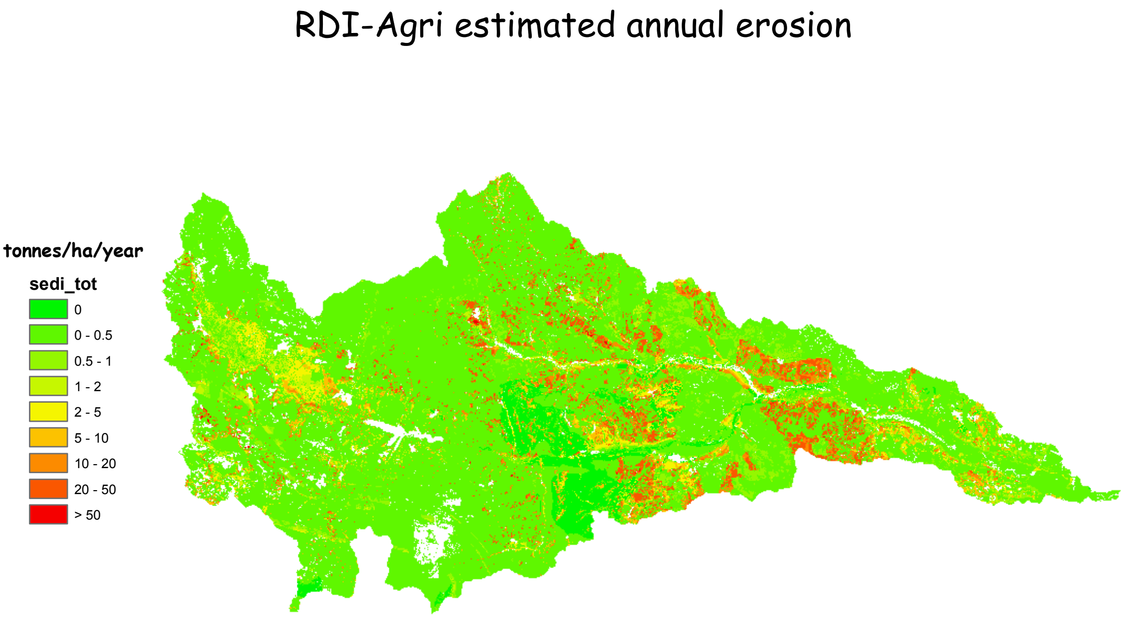
Comparison with ESI methodology



Although erosion risk is perhaps the most important component of sensitivity to desertification, the Environmental Sensitivity Index (ESI) also responds to other physical desertification risks, most notably salinity and fire. The ESI also differs in working at a much higher resolution, typically 50m, in comparison with the 1 km RDI grid. Thus, for example, the ESI map of forest areas shows patches with high sensitivity to fire within an area of uniformly low erosion risk. Outside forest areas, the RDI erosion risk has been combined with a salinity risk indicator, derived as described above. Because erosion occurs more on steep slopes, and salinity more on low slopes, we have created a single scale, in which standardised z-scores [(Value- Mean)/ Standard Deviation] for the Salinity Indicator are subtracted from z-scores for the RDI/PESERA Erosion Indicator. This RDI/Salinity Indicator (RSI) on the horizontal axis has been plotted against the ESI scores on the vertical axis. The red line shows that there is a good and consistent relationship between the two indices over almost the entire range of values. The anomalous falling curve on the extreme right of the graph can largely be ignored, as it contain only 0.05% of the values; while the vast majority of points in the broad central scatter, which contains over 90% of the values, are closely grouped around the red line relationship. There are also good relationships between the RDI Erosion indicator and mean ESI values derived at 50 m resolution for slope gradient, aridity, soil texture and erosion protection (essentially land cover/ land use). This shows that these main drivers of the RDI erosion indicator remain valid and relevant when the higher resolution values are used, so that scaling up for the change in resolution should give consistent results.

To date, these comparisons have only been completed for the Agri Basin, but this comparison should provide an inter-comparison between ESIs derived for different Target Areas, and thus help to justify the extension of this methodology to larger and other areas.

Estimated Erosion Risk in the Agri Basin


RDI-Agri estimated annual erosion

Health warning

No erosion map at a European scale can be based on detailed knowledge at every point. Not every factor of local importance can be included in a comprehensive model, and there are some anomalies which are inherent in limitations in the data. However, by applying a common methodology, based on physical understanding, throughout Europe, the map is able to indicate the major differences between regions, to highlight areas which are particularly at risk, and to provide a uniform basis for comparison of the erosion risks across national boundaries and climate zones.

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