(Proceedings of a conference held in Banff, Canada, 11–14 June 2012) (IAHS Publ. 354, 2012).

The applicability of black carbon for tracing soil erosion: fire impacts on landscape dynamics in Cyprus

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Abstract On the Mediterranean island of Cyprus, a series of both natural and anthropogenic factors has led to severe land degradation in the past, which now results in water shortage during the summer months. A combined approach of terrain mapping, unmanned aerial system (UAS) flight missions and chemical characterization of black carbon will permit the classification of hazardous locations in terms of potential fires and erosion processes. The emphasis of the upcoming surveys is concentrated on those catchments that are connected to one of the numerous valley dammed reservoirs. There, the use of black carbon as an erosion indicator will be examined to trace the paths of eroded material inside the watershed and to enable a reconstruction of process dynamics and local fire history.

Key words Mediterranean; post-fire erosion; unmanned aerial system; black carbon; Cyprus

INTRODUCTION

According to the current scientific consensus, global climatic conditions will change considerably in the coming decades and centuries (IPCC, 2007). Global and regional climate models project significant temperature increases and reduced annual precipitation for the eastern Mediterranean, primarily during spring to summer. Consequently, this area is recognized as a hot spot for climatic change (Giorgi, 2006), where increasing annual mean temperatures will exacerbate problems with regard to water supply (Fox *et al.*, 2007) and the intensity of forest fires (Pausas, 1999). The risk of climatically-induced changes in environmental conditions across the Mediterranean region increases the need for low-cost, technically uncomplicated and versatile, practical methods for environmental monitoring that can deliver reliable spatial and temporal comparisons at national and international scales (Morvan *et al.*, 2008).

Forest fires and post-fire erosion have serious impacts on soil characteristics and are considered the main drivers of degradation of forested areas across the Mediterranean region. Although a natural feature of Mediterranean ecosystems (Naveh, 1975), fires have developed an increasingly destructive potential in recent decades, particularly in combination with unadapted land use (Naveh, 2007). In the 1990s, 600 000 hectares of forest were destroyed annually across the Mediterranean by forest fires (Shakesby & Doerr, 2006). The summer droughts responsible for increasing the risk of forest fires recently caused crop shortfalls in wide areas of the Mediterranean, for example in the Iberian Peninsula in 2005 (García Herrera *et al.*, 2007), and led to saving measures and emergency water supply such as in Cyprus in 2008 (Michaelides & Pashiardis 2008). For the Eastern Mediterranean, detailed studies on forest fires and post-fire erosion are rarely found, and those that do exist focus on a small number of countries (e.g. Israel, Greece). Area-wide and publicly-available analyses for Cyprus have not existed until now. In addition, most investigations in the region have not been published in peer-review journals, since they are published by local forestry and environmental authorities in reports for the purpose of documentation. The analysis of forest fires with regard to their impact on landscape dynamics can both contribute to the understanding of ecosystems and their morphological developments in the past, and to understanding their potential development under environmental perturbations in the future (Gedye *et al.*, 2000).

THE SITUATION IN CYPRUS

Cyprus (Fig. 1) is an island situated in the Eastern Mediterranean Sea, west of Syria, and is divided into the northern Turkish-controlled area and the larger Republic of Cyprus in the south. The

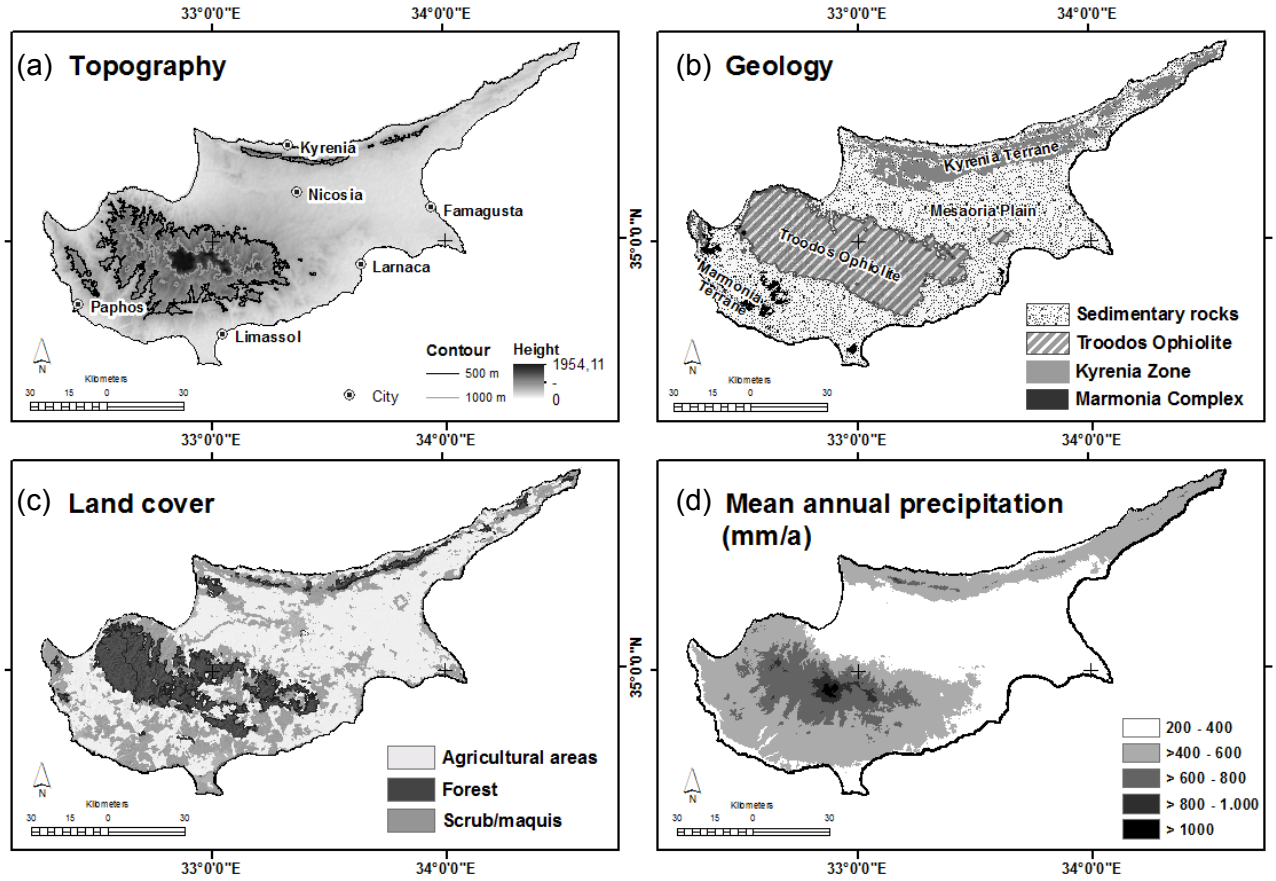

Fig. 1 Topography, geology, land cover and annual precipitation of Cyprus (Data sources: topography data from ASTER GDEM V2; land cover data from CLC2006; geology and precipitation data provided by Armin Duenkeloh/University of Wuerzburg).

geology of Cyprus (Fig. 1(b)) is dominated by the Troodos ophiolite, a sequence of former oceanic crust material, that now towers over the island up to 1952 m (Mount Olympus). The stratigraphy contains mantle and lava sequences as well as plutonic and sheeted dyke complexes (Varga & Moores, 1985). The much smaller Kyrenia range in the north consists of Permian to Miocene sedimentary rocks. A wide sedimentary plain is situated between these mountain ranges, and called the Mesaoria. The distribution and assemblage of soils indicates a long history of denudation and degradation. The Troodos mountain range is dominated by eutric-lithic Leptosols and eutric-skeletic Regosols. Eutric Cambisols and anthropic Regosols are primarily located in the valleys. The Mesaoria is dominated by calcic Luvisols, calcaric-lithic Leptosols and calcaric-leptic Regosols. Solitary occurrences of gleyic Solonets and vertic-leptic Calcisols are distributed all over the sedimentary rocks (Hadjiparaskevas, 2005).

Due to the Mediterranean climate, rainfall occurs from October to May. Annual precipitation is highly correlated with the topography of the island (Fig. 1(a) and (d)) but is also extremely variable (Fig. 2). Therefore, annual precipitation exceeds 1000 mm at some points in the Troodos Mountains, while the major part of the island can be considered semi-arid with values around 200–400 mm/year. The analysis of long-term data trends as well as the projections of regional climate models (RCM) both suggest an intensification of aridity and an increase of weather extremes across the eastern Mediterranean (Hadjinicolaou *et al.*, 2010).

In order to secure the water supply for domestic use and irrigation, more than 100 dams and reservoirs of different types, with a cumulative storage capacity of 300×10^6 m^3 were constructed in Cyprus during the last 70 years. The largest structure is the Kouris Dam with a capacity of

115×10^6 m^3. However, in 2008, after a series of four consecutive years with low precipitation, the storage volume of the major dams was reduced to less than 10%, meaning that the dams "were virtually empty" (Michaelides & Pashiardis, 2008). Due to these conditions, an expensive water transfer by boat from Greece had to be arranged to secure the domestic water supply and compensation payments were paid to farmers.

In the forested areas of the Troodos mountain range, wildfires and post-fire erosion exacerbate this critical situation by reducing the groundwater recharge rate of the aquifers located in this region. The most important aquifers are located in the fractured rocks of the ophiolite, as well as in sedimentary structures around the central Troodos. Re-occurring long-term droughts, a growing demand for water, as well as the reduced recharge of coastal aquifers due to the construction of dams has led to a reduction of the coastal groundwater tables and thus to an increased risk of sea water intrusion (European Environment Agency, 2009). Overall, 12 of 19 aquifers in southern Cyprus are already affected by, or are at risk of, saltwater intrusion. Severe salt water contamination has already occurred in the region of Larnaca, caused by the overexploitation of the Kiti aquifer for the purpose of agricultural irrigation (Milnes & Renard, 2004). In the southern part of the Troodos Mountains, the aquifers partially lie in the range of sedimentary structures; the groundwater there is already moderately saline. In the upper sections of the Kouris catchment, located in the central parts of the Troodos, depletion of groundwater due to irrigation methods has been reported (e.g. Boronina *et al.*, 2003).

About 19% of the island is covered with forest, but only half of that area is classified as high forest. State forests make up the major part (92% or 161 000 ha) and primarily consist of *Pinus brutia* (45%), reforestation areas (21%) and maquis vegetation (16.5%). Available fire statistics include all incidents in state forests. According to the forest fire statistics for 2001–2010, the main cause for forest fires on Cyprus was human activity, whether agricultural work (24%), fires caused by picnickers or travellers (16%), or arson (1%). Only 12% of all fires on Cyprus can be connected to natural causes such as lightning and 13% of all fires have unknown sources (Boustras *et al.*, 2008; Department of Forests, 2011). From 2000 to 2009, only 7% of all fires exceeded 5 ha in extent, and 83% affected only 1 ha, or less. The fires mainly occur in the fire season from April to November. Figure 2 shows the fire occurrence on Cyprus after a series of drought years. It can be argued that the large fire in 1998, as well as the increase of fire numbers in the subsequent years, is

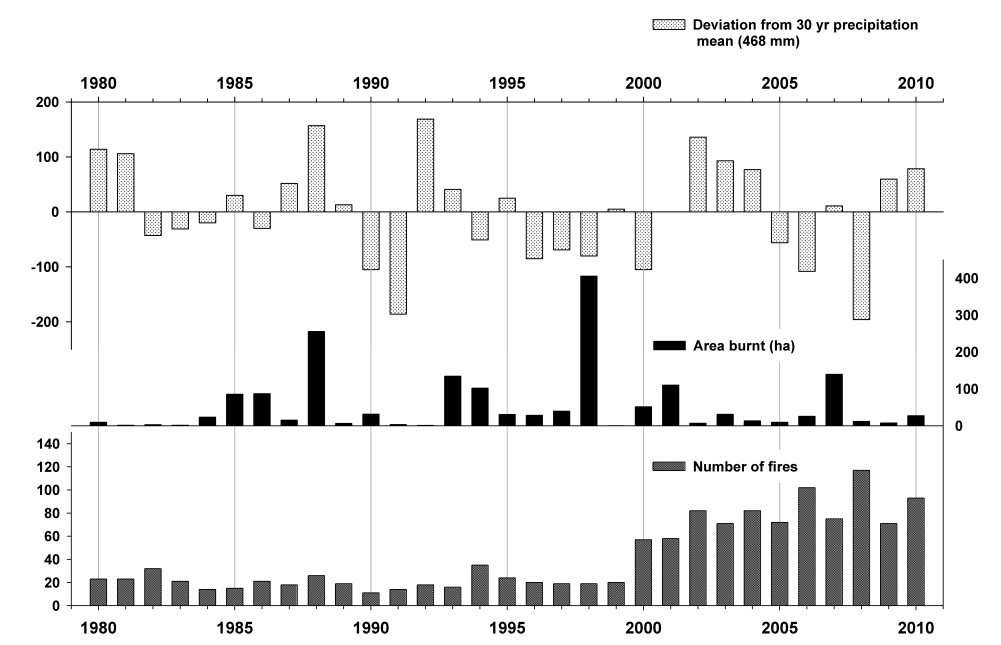

Fig. 2 Mean annual precipitation and fire statistics for Cyprus (1980–2010) (Data sources: Department of Forests, 2011; Cyprus Meteorological Service, 2011).

related to the increase in available fuel due to degraded vegetation. The obvious decrease in burnt area during the period 2001–2010, may be connected to the improvement and expansion of forest fire mitigation measures. These abatement options include the maintenance of forested areas, the construction of firebreaks, and the implementation of information campaigns for minimizing risky practices (Department of Forests, 2011).

POST-FIRE EROSION ASSESSMENT AND LOCAL FIRE RECONSTRUCTION METHODS

One primary object of fire-related surveys is assessing the impact of such landscape disturbance on erosion dynamics. Understanding the linkages between changing land cover and subsequent intensification of landscape dynamics have been a primary research objective in the Mediterranean for decades. Accordingly, a large number of articles cover these topics (see summaries of Boardman, 2006; Bakker *et al.*, 2008; García-Ruiz, 2010). Comparative studies of various locations across the Mediterranean have confirmed strong linkages between soil erosion rates and different land uses due to specific site parameters, the most important being vegetation cover (Cosmas *et al.,* 1997).

For any project that intends to analyse landscape dynamics, the mapping and monitoring of vegetation cover is therefore a fundamental task. Appropriate ground-cover information on a large scale can be derived from vegetation indices such as the Normalized Difference Vegetation Index (NDVI) that is commonly based on LANDSAT or NOAA data. But, due to the low resolution (60 m × 60 m) these data sources are not sufficient for applications at the erosion plot scale. Unmanned aerial systems (UAS) have the potential to link soil surveys and remote sensing data, especially in terms of "the scale and resolution gap" (Aber *et al.*, 2010). The application of unmanned aircraft can range from military use as drones to deployment in civilian projects, and these devices have been increasingly used for scientific purposes in recent years. Different kinds of UAS platforms can be equipped with a variety of sensors and are therefore adaptable to investigating many different scientific objectives. The most recent software developments even allow the generation of high-resolution elevation data from digital images (e.g. Haala *et al.*, 2010). Although numerous recent studies deal with the general issue of soil erosion across the Mediterranean region, the direct comparability of their results remains problematic due to the contrasting methods used to assemble the data. These methods include artificial irrigation and infiltration measurements (e.g. Seeger, 2007; Ries, 2010), permanently installed sediment traps and studies on retaining dams (e.g. Sirvent *et al.*, 1997; Romero Díaz *et al.*, 2007; Bellin *et al.*, 2009), and the conventional analysis of soil parameters on defined areas of investigation (plots) (e.g. Cammeraat, 2004; Brown *et al.*, 2009). Artificial tracer tests have, to date, been deployed less frequently due to the challenges associated with their implementation. For example, a recent study of soil erosion with synthetic magnetic tracers (Ventura *et al.*, 2002) reported the need to mimic the influence of size-dependent sorting during erosion processes. In this context, appropriate tracers require careful matching with the particle size characteristics of host soils and need to be able to mimic the natural transportability of soil particles taking account of density and particle interaction. As an alternative, natural environmental tracers seem to be more promising in terms of investigating fire signals. For example, the use of magnetism as a potential indicator of fire in sediment archives was investigated by Gedye *et al.* (2000). However, while magnetic peaks in sediment archives can be used as indications of fire, these do not allow the disentangling of the specific locations releasing soil and sediment post-fire.

In order to reconstruct system connectivity and sediment flux on a larger scale, geochemical fingerprinting can be used to establish the origin of deposited material. Rare earth elements are commonly used to specify individual source areas and to associate those to fractions within a sediment archive (e.g. Kimoto *et al.*, 2006). Fallout radionuclides are applicable for tracing erosion over recent time periods. The applicability of the different radionuclides (e.g. ^{137}Cs, unsupported ^{210}Pb and ^{7}Be) is determined by their specific half-life (e.g. Mabit *et al.*, 2008).

The immediate impact of forest fires is detectable on the basis of physical changes in vegetation, as well as in the alteration of soil parameters and properties (Koegel-Knabner, 2000), including pH, infiltration capacity or the stability of aggregates (Certini, 2005; Fox *et al.*, 2007; Knicker, 2007). The environmental impacts of forest fires have been the subject of a series of studies (e.g. Shakesby & Doerr, 2006; Cerdà & Doerr, 2008; Conedera *et al.*, 2009) using a range of research methods and techniques. According to Shakesby & Doerr (2006), the establishment of a uniform classification scheme for the extent of forest fires and their impacts on the soil surface is of particular relevance with regard to assisting the direct comparability of diverse studies. Since it is infeasible to measure the surface temperature during a natural fire, parameters that are recorded afterwards should be the basis for the categorization of various fire events. As the organic constituents of Mediterranean soils are heavily affected by fires in terms of both quality and quantity (Knicker *et al.*, 2006), they can be used to reconstruct the extent as well as the impact of forest fires. For instance, NMR spectroscopy can be used to assess directly the pyrogenic alterations of soil substrates and vegetation and, as such, has already been widely utilized by several case studies in the context of soil quality and organic matter content (Gonzalez-Perez *et al.*, 2004; Knicker *et al.*, 2006), primarily concentrating on carbon, nitrogen and phosphate dynamics. The use of NMR spectroscopy for biological indicators is particularly valuable for recalcitrant plant components, such as the aromatic lignins or condensed biomass in general (Koegel-Knabner, 2002). Lignins show specific properties that allow an estimation of fire temperatures as well as the reconstruction of taxonomic information (Whitlock & Larsen, 2002; Knicker, 2007). On account of their natural or pyrogenic hydrophobic properties, these components remain unaltered even in aquatic archives, qualifying them for use as tracers in environmental reconstructions (Conedera *et al.*, 2009).

PROJECT AIMS AND METHODS

The principal aim of one ongoing scientific project is the assessment of fire induced erosion on Cyprus and the potential implementation of targeted mitigation measures. Because of the rather unique environmental setting and the large number of artificial sediment archives available for analysis, the project is seeking to test the applicability of black carbon for tracing soil erosion in conjunction with fire as a landscape disturbance.

Erosion assessment

The main research questions driving ongoing work by a new research project are:

- To what extent does the magnitude of soil erosion in the Troodos Mountains depend on the specific impact of forest fires?
- How can the primary parameters that define the vulnerability of the area to forest fires be measured and differentiated?

The primary task is to evaluate the vulnerability of the forested areas towards fire. In order to determine where most fires appear and to examine their impact on landscape dynamics, the establishment and maintenance of a fire database is considered essential. Historic forest fires will be registered with respect to both their spatial and temporal distribution and evaluated in a GIS environment. A geodatabase with time series of precipitation distribution, long-term climate data and fire frequencies will be established and used to undertake comparisons between these data sets.

Based on the fire geodatabase, exemplary sites of forest fires and post-fire erosion will be selected in the Troodos area for more detailed investigation. A number of ideal locations have already been located within watersheds that are connected to one of the many valley-dammed reservoirs. At these sites, all mapping results are being documented in a mobile geographical information system. The mobile mapping device (Trimble Yuma) is a rugged outdoor computer with an integrated GPS, providing a higher resolution compared to standard handheld devices. The

primary tasks of these initial field surveys will be to identify and quantify sediment archives as well as to identify transport pathways and processes inside the respective catchments. Additionally, sets of soil samples will be collected from burnt and unburnt sites to determine location-specific parameters.

High resolution land-cover data that is needed for vegetation cover and fuel-load assessments will be provided by surveys of the APAESO project (Autonomous Flying Platforms for Atmospheric and Earth Surface Observations), conducted by members of the Cyprus Institute. UAS devices are used by the Cyprus Institute for a variety of scientific purposes, such as obtaining high-resolution multispectral remote sensing data to generate land-cover classifications.

Local fire reconstruction based on NMR

Due to the high number of dams (about 100) and the contrasting nature of the corresponding drainage basins, the project also aims to test the use of black carbon as an erosion indicator and as a tool for quantitative reconstruction of historic process dynamics. To this end, NMR (nuclear magnetic resonance) spectral analysis of soil organic matter will be used to draw conclusions on local fire conditions, and to trace the sediment delivery pathways down to valley-dammed reservoirs. Estimation of the long-term sediment yields of the specific catchments will be based on the gross sediment accumulation in the dams together with information on the year of construction and retention efficiency. A sediment chronology for the dam sites will be based on the collection of cores during the summer months. The data provided by the use of black carbon as an erosion tracer will be used to support catchment modelling for the eastern Mediterranean, for decision making associated with the targeting of forest fire mitigation measures.

PERSPECTIVE

The project briefly described above is still under development and its funding is currently low to non-existent. Initial field surveys will start in March 2012. The purpose of this contribution is to increase awareness of this particular application of black carbon as an erosion tracer and to provide an opportunity for wider researchers to feedback recommendations in terms of the research methodology.

Acknowledgements The authors would like to thank the reviewers for their valuable comments and recommendations for improving the manuscript. We also thank Armin Duenkeloh (University of Wuerzburg) for providing parts of his GIS data collection.

REFERENCES

Aber, J. S., Marzolff, I. & Ries, J. B. (2010) *Small-format Aerial Photography – Principles, Techniques and Geoscience Applications*. Elsevier, 268 pp.

Bakker, M. M., Govers, G., van Doorn, A., Quetier, F., Chouvardas, D. & Rounsevell, M. (2008) The response of soil erosion and sediment export to land-use change in four areas of Europe: The importance of landscape pattern. *Geomorphology* 98 (3-4), 213–226, 10.1016/j.geomorph.2006.12.027.

Bellin, N., van Wesemael, B., Meerkerk, A., Vanacker, V. & Barbera, G. G. (2009) Abandonment of soil and water conservation structures in Mediterranean ecosystems: A case study from south east Spain. *Catena* 76(2), 114–121, doi:10.1016/j.catena.2008.10.002.

Boardman, J. (2006) Soil erosion science: reflections on the limitations of current approaches. *Catena* 68(2-3), 73–86, doi:10.1016/j.catena.2006.03.007.

Boronina, A., Renard, P., Balderer, W. & Christodoulides, A. (2003) Groundwater resources in the Kouris catchment (Cyprus): data analysis and numerical modelling. *J. Hydrol.* 271(1-4), 130–149, doi:10.1016/s0022-1694(02)00322-0.

Boustras, G., Bratskas, R., Pourgouri, S., Michaelides, A., Efstathiades, A. & Katsaros, E. (2008) A Report on Forest Fires in Cyprus. *Australasian Journal of Disaster and Trauma Studies* 2.

Brown, A. G., Carey, C., Erkens, G., Fuchs, M., Hoffmann, T., Macaire, J.-J., Moldenhauer, K.-M. & Walling, D. E. (2009) From sedimentary records to sediment budgets: multiple approaches to catchment sediment flux. *Geomorphology* 108(1-2), 35–47, doi:10.1016/j.geomorph.2008.01.021.

Cammeraat, E. L. H. (2004) Scale dependent thresholds in hydrological and erosion response of a semi-arid catchment in southeast Spain. *Agriculture, Ecosystems & Environment* 104(2), 317–332, doi:10.1016/j.agee.2004.01.032.

Cerdà, A. & Doerr, S. H. (2008) The effect of ash and needle cover on surface runoff and erosion in the immediate post-fire period. *Catena* 74(3), 256–263, 10.1016/j.catena.2008.03.010.

Certini, G. (2005) Effects of fire on properties of forest soils: a review. *Oecologia* 143 (1), 1–10, 10.1007/s00442-004-1788-8.

Conedera, M., Tinner, W., Neff, C., Meurer, M., Dickens, A. F. & Krebs, P. (2009) Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation. *Quaternary Science Reviews* 28(5-6), 555–576, doi: 10.1016/j.quascirev.2008.11.005.

Cyprus Meteorological Service (2011) Meteorological Reports. Ministry of Agriculture, Natural Resources and Environment, Nicosia, Cyprus. Official website: http://www.moa.gov.cy.

Department of Forests (2011) Forest fires statistics. Ministry of Agriculture, Natural Resources and Environment, Nicosia, Cyprus. Official website: http://www.moa.gov.cy.

European Environment Agency (2009) Water resources across Europe – confronting water scarcity and drought, EEA. 2/2009.

Fox, D. M., Darboux, F. & Carrega, P. (2007) Effects of fire-induced water repellency on soil aggregate stability, splash erosion, and saturated hydraulic conductivity for different size fractions. *Hydrol. Processes* 21 (17), 2377–2384, 10.1002/hyp.6758.

Garcia-Herrera, R., Paredes, D., Trigo, R. M., Trigo, I. F., Hernandez, E., Barriopedro, D. & Mendes, M. A. (2007) The outstanding 2004/05 drought in the Iberian Peninsula: associated atmospheric circulation. *J. Hydromet.* 8(3), 483–498.

García-Ruiz, J. M. (2010) The effects of land uses on soil erosion in Spain: a review. *Catena* 81(1), 1–11, doi: 10.1016/j.catena.2010.01.001.

Gedye, S. J., Jones, R. T ., Tinner, W., Ammann, B. & Oldfield, F. (2000) The use of mineral magnetism in the reconstruction of fire history: a case study from Lago di Origlio, Swiss Alps. *Palaeogeography, Palaeoclimatology, Palaeoecology* 164(1-4), 101–110, doi:10.1016/s0031-0182(00)00178-4.

Giorgi, F. (2006) Climate change hot-spots. *Geophys. Res. Lett.* 33(8), L08707, 10.1029/2006gl025734.

Haala, N., Hastedt, H., Wolf, K., Ressl, C. & Baltrusch, S. (2010) Digital photogrammetric camera evaluation generation of digital elevation models. *Photogrammetrie – Fernerkundung – Geoinformation* 2010(2), 99–115, 10.1127/1432-8364/2010/0043.

Hadjinicolaou, P., Giannakopoulos, C., Zerefos, C., Langem, M. A., Pashiardis, S. & Lelieveld, J. (2010) Mid-21st century climate and weather extremes in Cyprus as projected by six regional climate models. *Reg. Env. Change* doi: 10.1007/ s10113-010-0153-1

Hadjiparaskevas, C. (2005) Soil survey and monitoring in Cyprus. *European Soil Bureau-Research Report* 9, 97–101.

IPCC (2007) Climate Change 2007: The Physical Science Basis. In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller (eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, p. 996. Cambridge, United Kingdom and New York, NY, USA.

Kimoto, A., Nearing, M. A., Shipitalo, M. J. & Polyakov, V. O. (2006) Multi-year tracking of sediment sources in a small agricultural watershed using rare earth elements. *Earth Surface Processes and Landforms* 31(14), 1763–1774, 10.1002/esp.1355.

Knicker, H. (2007) How does fire affect the nature and stability of soil organic nitrogen and carbon? A review. *Biogeochemistry* 85(1), 91–118, 10.1007/s10533-007-9104-4.

Koegel-Knabner, I. (2000) Analytical approaches for characterizing soil organic matter. *Organic Geochemistry* 31(7-8), 609–625, doi:10.1016/s0146-6380(00)00042-5.

Kosmas, C., Danalatos, N., Cammeraat, L. H., Chabart, M., Diamantopoulos, J., Farand, R., Gutierrez, L., Jacob, A., Marques, H., Martinez-Fernandez, J., Mizara, A., Moustakas, N., Nicolau, J. M., Oliveros, C., Pinna, G., Puddu, R., Puigdefabregas, J., Roxo, M., Simao, A., Stamou, G., Tomasi, N., Usai, D. & Vacca, A., (1997) The effect of land use on runoff and soil erosion rates under Mediterranean conditions. *Catena* 29(1), 45–59, doi:10.1016/s0341-8162(96)00062-8.

Mabit, L., Benmansour, M. & Walling, D.E. (2008) Comparative advantages and limitations of the fallout radionuclides 137Cs, 210Pbex and 7Be for assessing soil erosion and sedimentation. *J. Environmental Radioactivity* 99(12), 1799–1807, 10.1016/j.jenvrad.2008.08.009.

Michaelides, S. & Pashiardis, S. (2008) Monitoring drought in Cyprus during the 2007-2008 hydrometeorological year by using the standardized precipitation index (SPI). *European Water* 23/24, 123–131.

Milnes, E. & Renard, P. (2004) The problem of salt recycling and seawater intrusion in coastal irrigated plains: an example from the Kiti aquifer (Southern Cyprus). *J. Hydrol.* 288 (3-4), 327–343, doi: 10.1016/j.jhydrol.2003.10.010.

Morvan, X., Saby, N. P. A., Arrouays, D., Le Bas, C., Jones, R. J. A., Verheijen, F. G. A., Bellamy, P. H., Stephens, M. & Kibblewhite, M. G. (2008) Soil monitoring in Europe: A review of existing systems and requirements for harmonisation. *Sci. Total Environ.* 391(1), 1–12, 10.1016/j.scitotenv.2007.10.046.

Naveh, Z. (1975) The evolutionary significance of fire in the Mediterranean region. *Plant Ecology* 29(3), 199–208, 10.1007/bf02390011.

Naveh, Z. (2007) Fire in the Mediterranean – a landscape ecological perspective. In: *Transdisciplinary Challenges in Landscape Ecology and Restoration Ecology – Fire in Ecosystems Dynamics* (ed. by J. F. Goldammer & M. J. Jenkins), 1–20. Springer Netherlands.

Pausas, J. G. (1999) Response of plant functional types to changes in the fire regime in Mediterranean ecosystems: A simulation approach. *J. Vegetation Science* 10(5), 717–722, doi:10.2307/3237086.

Pausas, J. G. (2004) Changes in fire and climate in the Eastern Iberian Peninsula (Mediterranean Basin). *Climatic Change* 63 (3), 337–350, doi:10.1023/B:CLIM.0000018508.94901.9c.

Ries, J. B. (2010) Methodologies for soil erosion and land degradation assessment in Mediterranean-type ecosystems. *Land Degradation & Development* 21(2), 171–187, doi:10.1002/ldr.943.

Romero-Díaz, A., Alonso-Sarriá, F. & Martínez-Lloris, M. (2007) Erosion rates obtained from check-dam sedimentation (SE Spain). A multi-method comparison. *Catena* 71(1), 172–178, doi: 10.1016/j.catena.2006.05.011.

Seeger, M. (2007) Uncertainty of factors determining runoff and erosion processes as quantified by rainfall simulations. *Catena* 71(1), 56–67, doi:10.1016/j.catena.2006.10.005.

Shakesby, R. A. & Doerr, S. H. (2006) Wildfire as a hydrological and geomorphological agent. *Earth-Science Reviews* 74(3-4), 269–307, doi:10.1016/j.earscirev.2005.10.006.

Sirvent, J., Desir, G., Gutierrez, M., Sancho, C. & Benito, G. (1997) Erosion rates in badland areas recorded by collectors, erosion pins and profilometer techniques (Ebro Basin, NE-Spain). *Geomorphology* 18(2), 61–75, doi: 10.1016/s0169-555x(96)00023-2.

Varga, R. J. & Moores, E. M. (1985) Spreading structure of the Troodos ophiolite, Cyprus. *Geology* 13(12), 846–850, 10.1130/0091-7613(1985)13<846:ssotto>2.0.co;2.

Ventura, E., Nearing, M. A., Amore, E. & Norton, L. D. (2002) The study of detachment and deposition on a hillslope using a magnetic tracer. *Catena* 48(3), 149–161, doi: 10.1016/s0341-8162(02)00003-6.

Whitlock, C. & Larsen, C. (2002) Charcoal as a fire proxy. In: *Tracking Environmental Change Using Lake Sediments 03; Terrestial, Algal, and Siliceous Indicators,*(ed. by J. P. Smol, H. J. B. Birks & W. M. Last), 75–97. Kluwer Academic Publishers, Dordrecht, Netherlands.