Catena 150 (2017) 192–205

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Coupling of phenological information and simulated vegetation index time series: Limitations and potentials for the assessment and monitoring of soil erosion risk

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ARTICLE INFO

Article history:
Received 1 April 2016
Received in revised form 6 November 2016
Accepted 7 November 2016
Available online xxxx

Keywords:
Soil erosion
Monitoring
STARFM
NDVI
Phenology
Soil cover

ABSTRACT

Monitoring of soils used for agriculture at frequent intervals is crucial to support decision making and refining soil policies especially in the context of climate change. Along with rainfall erosivity, soil coverage by vegetation or crop residues is the most dynamic factor affecting soil erosion. Parcel-specific soil coverage information can be derived by satellite imagery with high geometric resolution. However, their usable number is mostly, due to cloud cover, not representative for the phenological characteristics of vegetated classes. To overcome temporal constraints, spatial and temporal fusion models, such as STARFM, are increasingly applied to derive high-resolution time series of remotely sensed biophysical parameters, based on fine spatial/coarse temporal resolution imagery, such as Landsat, and coarse spatial/fine temporal resolution imagery, such as MODIS. In this context, the current study introduces an evaluation scheme for simulated vegetation index time series which enables the assessment of their performance during multiple phenological phases. The evaluation scheme is based on Germany-wide available spatial predictions of phenological phases as well as RapidEye imagery and parcel-specific crop-type information. The evaluation results show that the simulation accuracy is basically controlled by the temporal distance between MODIS and Landsat base pairs, as well as the ability of the actual Landsat image to properly represent the phenological phase of the Landsat image simulated by MODIS. In addition, we discuss the potential of simulated index times series and corresponding phenological information for the dynamic (1) definition of temporal windows where soils are potentially covered by no, sparse or dense vegetation or crop residues and (2) parameterization of soil erosion models. The database thus obtained opens up new possibilities for an efficient and dynamic erosion monitoring, which can support soil protection and hazard prevention.

1. Introduction

Soil erosion by water on agricultural land is a global phenomenon with important economic and environmental consequences, affecting soil functioning, such as biogeochemical cycling, hydrology or crop productivity (Govers et al., 2014). According to Panagos et al. (2015), the replacement cost of soil lost to water erosion in Europe can be estimated at about USD 20 billion per year.

The most important dynamic factors of soil erosion are rainfall erosivity and soil coverage by vegetation or crop residues (Panagos et al., 2014a). Since soil erosion is an event-based process and due to the spatial and temporal variability of soil erosion (Prasuhn, 2011; Evans, 2013; Aiello et al., 2015), it is a challenge to identify relevant time periods (Li et al., 2014; Alexandridis et al., 2015) with a view to predicting up-to-date *and* long-term "hotspots where serious erosion is occurring" (Boardman, 2006). Monitoring of soils affected by erosion events at frequent intervals is needed to obtain an understanding of soil erosion processes regarding land use and climate change (Evans, 2013; Prasuhn, 2011). This is crucial to support decision making and

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http://dx.doi.org/10.1016/j.catena.2016.11.016
0341-8162/

refining soil policies (Li et al., 2014; Robinson, 2015), especially in the context of climate change (Routschek et al., 2014a,b). In Europe, this concerns regulations relating to land management practices and economic incentives, mostly in the frame of the European Union's Common Agricultural Policy (CAP; Volk et al., 2010). However, long-term monitoring of erosion features is rare due to the short-term character of low-budget research projects (Prasuhn, 2011) or due to human resource constraints within state authorities (Feldwisch, 2015).

Fig. 1 illustrates the spatiotemporal dynamic of soil coverage, which differs as a consequence of phenological development. The photograph was taken on June 19th 2013, shortly after a high-intensity rainfall event and shows two parcels with almost identical topographic and soil conditions. While the left-hand parcel is fully covered by winter wheat, the right-hand parcel is characterized by emerging maize. Due to the lack of protective cover, slope-related rills and accumulation zones of topsoil material are visible there.

During a typical vegetation cycle of crop types, the vegetation coverage is relatively low during early phenological phases, but increases until the maximum vitality of the plants is reached. Shortly after harvest, crop residue coverage is high, but decreases due to disintegration of the senescent plant components. Depending on the type of soil cultivation, soil is either not covered or (partly) protected by mulch cover.

The phenological development of crops and corresponding soil coverage information can be monitored using multi-spectral satellite imagery (de Araujo Barbosa et al., 2015). A frequently applied approach is the building of statistical models between observed soil coverages and specific multi-spectral indices (Gitelson, 2013), which result from the ratio of at least two spectral bands (Gerstmann et al., 2016b). Vegetation indices, calculated from the reflectance in the spectral wavelength range between red (*RED*) and near-infrared (*NIR*), are most sensitive to differences in fractional vegetation coverage (*FVC*) due to the abrupt reflectance rise caused by the vegetation's chlorophyll in *NIR* (Tucker, 1979). The normalized difference vegetation index (*NDVI*; Rouse et al., 1974) is the most popular vegetation index and has been found to be accurate in predicting soil coverage by green vegetation (Gitelson, 2013; Yang et al., 2013; Vrieling et al., 2008; Vrieling et al., 2014; Prabhakara et al., 2015). *NIR* and *RED* bands are also used for the detection of bare soils (BS; Cui et al., 2014; Fox et al., 2004). The estimation of crop residue coverages (*CRC*) is based on short wave infrared (*SWIR*) spectral information that is approximately 2100 nm where cellulose and lignin show a specific absorption feature (Zheng et al., 2014).

On the basis of remotely sensed and freely available imagery of coarse spatial/fine temporal resolution, such as MODIS[1] or MERIS[2], the time series of biophysical parameters enable a dynamic soil erosion risk assessment, which considers seasonal, monthly or almost weekly vegetation coverage variations on a regional or sub-continental scale (e.g., Symeonakis and Drake, 2010; Panagos et al., 2012; Guerra et al., 2014; Vrieling et al., 2014; Alexandridis et al., 2015). The monitoring of parcel-specific soil coverage information requires the operational availability of satellite imagery with fine temporal and geometric resolution, as well as with a free data distribution policy. Even though "there is currently a plethora of [optical] sensors for mapping vegetation patterns . . . " (Panagos et al., 2014b), the number of usable fine resolution imagery is mostly, due to cloud cover, not "representative for the phenological characteristics of vegetated classes" (Aiello et al., 2015). This especially concerns imagery of the Landsat family, which, for decades has offered the only data with a free distribution policy and fixed temporal repetition (Houborg et al., 2015). However, "the sparse and unbalanced distribution of acquisition dates [... limits ...] its application in monitoring of long-term phenology change" (Tian et al., 2013).

To overcome temporal constraints, spatial and temporal fusion methods are increasingly applied to derive fine resolution time series of remotely sensed biophysical parameters. They combine coarse spatial/fine temporal and fine spatial/coarse temporal resolution imagery (Meng et al., 2013; Gao et al., 2015; Chen et al., 2015; Zhang et al., 2015). The spatial and temporal adaptive reflectance fusion model (STARFM) is one of the most widely-used spatial and temporal fusion algorithms (Gevaert and Garcia-Haro, 2015) and was developed to blend Landsat and MODIS imagery to generate synthetic Landsat surface reflectance data of fine spatial/fine temporal resolution (Gao et al., 2006). Although the STARFM is particularly considered suited to "capture reflectance changes caused by phenology" (Zhu et al., 2010), it is less appropriate when changes occur in land cover types (Huang and Zhang, 2014). The actual prediction accuracy depends on the selection of input image pairs, as well as their number and temporal distance (Olexa and Lawrence, 2014; Zhu et al., 2010). This means that the usability of simulated time series for soil coverage monitoring is restricted, since it is not known how the intra- and inter-annual dynamics of different crops can be explained by corresponding MODIS and Landsat image pairs. Thus, a thorough evaluation of the limits of the method especially in the context of agricultural settings is still needed (Lobell, 2013; Förster et al., 2015).

Regarding the example of a study site in Central Germany, this study covers three topics:

1. We show how simulated vegetation *NDVI* time series of fine temporal and geometric resolution and corresponding phenological crop information can be coupled.
2. We introduce a phenological evaluation scheme for such simulated *NDVI* time series.
3. We demonstrate how parcel-specific *NDVI* profiles can be dynamically derived for specific days of the year (DOYs) and phenological phases.

Finally, the results are discussed in the context of operational and parcel-specific assessment and monitoring of soil erosion risk by water.

2. Materials and methods

2.1. Study site

The study site is located in the German Federal State of Saxony-Anhalt approximately 30 km north of the city of Halle (Saale) (Fig. 2a and b). Due to the fertile soils of the study area (chernozems), the study site is characterized by intensive agricultural land use. The soils are at high risk of erosion because of heterogeneous landscape morphology, the erodibility of the dominant loess substrate and occurring intense rainstorm events (Möller et al., 2012). The most frequently grown crop types within the study site are winter wheat (WW; *Triticum aestivum* L.), winter barley (WB; *Secale cereale* L.), winter rapeseed (WR; *Brassica napus* L.), maize (MA; *Zea mays* L.) and common beet (CB; *Beta vulgaris*). Fig. 2c and d illustrates typical relations of crop type-specific area percentages in the study site for 2011 and 2012.

2.2. Data

2.2.1. Landsat and MODIS

For the study area, five multi-spectral Landsat 5 TM images (DOYs 112, 128, 208, 272 and 288) and one Landsat 7 ETM+ image (DOY 232) for 2011 with a pixel size of 30×30 m^2 were freely downloaded

[1] Moderate Resolution Imaging Spectroradiometer (http://modis.gsfc.nasa.gov).
[2] MEdium Resolution Imaging Spectrometer (https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat/instruments/meris).