Hydrol. Earth Syst. Sci. Discuss., 11, C1853–C1869, 2014
www.hydrol-earth-syst-sci-discuss.net/11/C1853/2014/

Hydrology and Earth System Sciences Discussions
Open Access

Interactive comment on "Monitoring of riparian vegetation response to flood disturbances using terrestrial photography" *by* K. Džubáková et al.

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Received and published: 16 June 2014

Joint Response to Anonymous Referees 1-3

The aim of our paper is to present a quantification of the immediate response of riparian vegetation to flood disturbance in a reach of a gravel-bed braided river by vegetation indices estimated using data from a recently installed terrestrial camera system with near-infrared sensitivity. The system was set up in the Maggia River in southern Switzerland in 2008 and this is the first paper reporting analyses of images collected there. From our point of view, the novelty of this work lies in (a) the use of near-infrared NIR sensitive camera monitoring of an alluvial system consisting of water, sediment and vegetated surfaces; (b) high spatial resolution of the images which allows detailed

identification of individual plants; and (c) continuous (daily) monitoring which allows the spatial analysis of short-term response before and after individual large floods in terms of both vegetation enhancement and damage.

The paper was reviewed by three anonymous referees. We address the main issues raised by the reviews in a joint response here and indicate how we will deal with them in the revision of our manuscript. Editorial corrections and suggestions by the referees are not discussed and will all be implemented. We only cite new papers in this response which expand the background of our work and/or support new statements/results. These will be added to the reference list in the revised manuscript.

1. Context of vegetation monitoring with NIR sensitivity

Vegetation indices are developed for the quantification of the vegetation signal in land surface images from remote sensing. They are based on reflectance properties of leaves and canopy structure in general in different wavebands. The available spectral bands of the sensor determine the selection of possible indices for analysis. Cameras are broadband sensors sensitive in the red-green-blue (RGB) visible bands only. However, for vegetation monitoring it is useful to have the near-infrared (NIR) band which is sensitive to chlorophyll in leaves and canopy structure. Vegetation indices which use the NIR band have become the most popular for vegetation growth/vigour applications, examples are the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI) which have become standard products of the Terra and Aqua satellites with MODIS (Moderate Resolution Imaging Spectroradiometer) on board.

For ground-based vegetation monitoring by cameras it is therefore of general advantage to expand photography from the RGB range to the NIR (e.g. Ritchie et al., 2008; 2010), as an alternative to infrared/thermal cameras which are costly and have a much lower pixel resolution than off-the-shelf digital cameras. This is what our camera monitoring system has been designed to do. To our knowledge this is one of the first applications of continuous floodplain monitoring with NIR-sensitivity by cameras. Our analysis is by necessity restricted to a selection of the most commonly used vegetation indices in the literature which use broadband reflectance information (RGB and NIR), like NDVI. Although narrowband vegetation indices have been shown to be more suitable for the prediction of leaf pigment content (e.g. Sims and Gamon, 2002; Berni et al., 2009; Zarco-Tejada et al., 2009), they require reflectance measurements with a high spectral frequency resolution, which cameras do not provide. On the other hand broadband indices such as NDVI were found to be a sensitive indicator of canopy greenness and chemical content in sparse canopies, such as ours (e.g. Gamon et al., 1995).

Finally, it is important to state upfront that in our images we are analyzing heterogeneous vegetation cover in a highly dynamic environment. This is in fact the biggest difference to most published literature on camera monitoring of vegetation, where particular species or canopies are being studied in isolation (e.g. Ahrends et al., 2008; Richardson et al., 2009; Rithcie et al., 2008; 2010; Mizunuma et al., 2011; Nagai et al., 2012). We are aiming for robust indices that recognize different types of surfaces, like open water and gravel as well as vegetation, with a range of sizes and leaf densities because all of these surfaces are on our floodplain and need to be quantified (see Fig 1 below). The selection and use of vegetation indices for quantifying floodplain change in our paper has to be seen from this perspective. Change detection follows the strategies and concepts laid out by Kennedy et al. (2009).

2. Which index is the best?

It is tempting to ask which index from our selection is the best for the problem at hand. In the review of our paper one referee asked “because the paper is looking at fine-scale, short-term vegetation dynamics, one would expect the priority [of the paper] to be determining which index most reliably represents vegetation activity” (Referee 1, C737). The referee goes on to argue that the choice of GNDVI as the ideal index based on its agreement with the other indices is problematic. The main reason being that the agreement between the indices depends on the bands used in their estimation in addition to NIR, i.e. in our case R or G, or both (like in CVI). The referee is right

in stating that the reason why GNDVI has the lowest average disagreement with the other indices is because it agrees best with CVI. This is in fact true for all other (green) G-based indices as well, as can clearly be seen in Table 3 in our manuscript. From this point of view it is indeed the CVI index which uses the R, G and NIR bands that is the “tie-breaker”. The referee is concerned that the message gleaned from this may that any G-based index is more suitable than an R-based index, which would be inaccurate. In fact studies have found that a combined G-R index (e.g. the GRVI index without NIR information) is more correlated with an estimate of maximum photosynthetic rate for a forest canopy (Nagai et al., 2012) may allow accurate crop growth estimates (Ritchie et al., 2010).

We would like to clearly state at this point that our intention is not to choose the single “best” index. We do not intend to transmit the message with our paper that GNDVI or any other green index is better than the others. Rather, we are aiming to indentify the direction and magnitude of change in photosynthetic activity and vegetation vigour insofar they are captured by a range of broadband vegetation indices which use the NIR band and which correspond to our subjective selection from the literature.

We believe that one of our most interesting outputs is in fact the series of maps showing the spatial distribution of the agreement between the indices in identifying vegetation damage for each flood in Figure 4 in our manuscript (right panels). Here we can identify areas in the floodplain where all indices agree on the direction of change. This information is much more robust and useful than that of a single “best” index. The reason why we only show the results for GNDVI in Figure 3 in our manuscript is that the GNDVI results are middle-of-the-road, giving the highest agreement in spatial predictions with the other 6 indices. In the revision of the manuscript we will make an effort to make it clear that (a) we are not showing GNDVI because it is the best index; and (b) we are in fact interested in seeing the spatial performance in capturing change after floods for a range of different indices which are commonly used. This is the added information which we want to take advantage of.

3. Field validation of vegetation indices

One way to resolve the question of the appropriateness of the different vegetation indices is to validate them in the field. This was also suggested by Referee 1 (C737-C738). Validation of broadband indices by camera monitoring is commonly done by checking if they are able to capture key phonological events, e.g. date of budding, flowering, senescence (e.g. Ahrends et a., 2008; Crimmins and Crimmins, 2008; Richarson et al., 2007), or if they correlate with estimates of primary productivity and carbon fluxes measured by flux towers (e.g. Ahrends et al., 2008; Richardson et al., 2009; Mizunuma et al., 2011; Nagai et al., 2012). Our aim however is to capture the distinction between gravel/water surfaces, plants and the change in their "greenness", i.e. water use efficiency and photosynthetic activity. This makes validation in the traditional sense very difficult in our study. There are basically two options: validation of the vegetation index itself and validation of the predicted change.

(1) Validation of the vegetation index. Vegetation indices divide the pixels in the R-G-B-NIR space into typical surface units by their reflectance. It is indeed true, as Referee 1 indicates (C737), that this space, as given by the digital numbers contained in the camera pixel brightness, can be verified in the field with spectrometer measurements. We have in fact planned to do these measurements in the autumn of 2014 with a field spectroradiometer (FieldSpec4 Standard Resolution, ASD Instruments). The procedure is to do concurrent measurements of spectral reflectance of typical surface combinations of the three prime surfaces (water, gravel, vegetation) and of different vegetation species compositions and ages in the field at the time when camera images are taken. This step has not been done to-date simply because we do not own a spectroradiometer and we needed to develop a collaboration to take these measurements. We will report on these comparisons in our next publication.

Referee 2 (C1119) asks why "a comparison of the present methodology with other techniques, e.g. satellite are not done". First of all, a comparison with satellite data was not within the scope of our study because the most common satellite vegetation

products like NDVI and EVI from MODIS have an insufficient accuracy and spatial resolution to be useful in our settings. The Maggia is a valley with very steep hillsides with a floodplain of maximum 400 m in width (usually much less). Within this width we are looking to capture small scale variability in floodplain surfaces only. Under these conditions satellite data are not as useful as they have been in studies of other large river systems in valley plains, e.g. the Tagliamento (see Bertoldi et al., 2011a; 2011b cited in manuscript). We can however imagine that newer satellite data obtained from QuickBird, GeoEye, Worldview, or Pleiades, which have comparable precision and frequency of data acquisition, can be useful for monitoring vegetation change in the future. It must be stressed that we consider satellite and terrestrial data to provide complementary information. Our ground-based monitoring needs some maintenance and includes a potential risk of data loss for longer time periods due to its remote operation; satellite data on the other hand have an un-adjustable time of data recording and are limited by clouds. However, both are valuable sources of remotely sensed information for riparian vegetation studies (Durfour et al., 2012).

(2) Validation of the predicted change. Change in the fundamental surface cover (vegetation scouring) after floods can be at least qualitatively validated in the images. An example is shown in Fig 2 below. Vegetation scour is recognizable when images before and after a flood are being compared. We were not able to analyze the change in herbaceous cover because the grass on the clearings is sparse and thus difficult to capture accurately by our system. Compact herbaceous cover is located only under trees where sand is deposited during floods. We will add Fig 2 to the revised manuscript to illustrate the spatial patterns of erosion and vegetation damage.

Another option suggested by Referee 1 (C737) is to do "field validation on some basic measure of biomass". We have done some preliminary stratification of vegetation height and can conclude that high absolute values of the vegetation indices are reasonably correlated with canopy height with higher leaf area and more complex canopy structure. We also see some potential in validating change in terms of post-flood water use captured by vegetation indices in larger trees by directly measuring it. We have done some preliminary measurements of stomatal conductance on a number of Salix eleagnos on our gravel bar during a two week period in spring 2013, and we are planning to expand this to continuous sap flows measurements on larger trees to capture the water use efficiency of the plants when they are under water stress during droughts (low flow periods). We expect this to be useful for the validation of the indices and predicted change in the future.

4. Camera settings and image analysis

The reviewers requested more information about the camera settings and image analysis (Referee 1, C738, C741; Referee 2, C1119, Referee 3, C1379). We will add some of the following explanations to the revised manuscript, while keeping our main focus on the analysis and interpretation of floodplain change and not on the sensor and monitoring technology.

The two cameras are placed next to each other in a weather-proof box. Photographs are triggered with a Timer Remote Control every 24 hrs at 11:00 UTC. The images are stored locally in the camera on CF memory cards. The box is placed on a steep rocky ridge above the river to give a good an unobstructed view of the floodplain at the highest angle we could safely get to. The depression angle to the centre of the image on the floodplain is 25 deg, the distances are listed in the manuscript. The camera box is accessible only by foot, along a steep mountain path. At the daily sampling resolution we have found that the original Canon batteries Li-Ion 700 mAh lasted at least 3 months (depending on temperature), so we opted not to power the system with solar panels, but visit the camera location 3 times a year to replace batteries, download the images, and perform basic maintenance (cleaning). These are the only trips required to the camera location, so after instrument and installation costs are accounted for, the maintenance costs of the system are very low.

The optimal settings of the cameras were tested extensively during 2007. Unlike studies which use cameras with automatic settings or webcams (e.g. Ahrens et al., 2008; Richardson et al., 2007; 2009; Ritchie et al., 2008; 2010; Mizunuma et al., 2011), we fixed all adjustable settings manually (except white balance) so that we can directly compare the digital numbers DNs (brightness at sensor) in the RGB bands and the NIR band with each other in all images without transformations. We prefer to avoid any image normalization (Referee 1, C741) of the kind done by Richardson et al. (2007) and others prior to analysis because this opens a degree of freedom in the relation between RGB and NIR bands. However, we will look closer into the effect of DN normalization in the future.

To fix the key camera settings we looked at the image DNs of the floodplain in the R-NIR space for a range of typical light conditions. We explored the aperture and time setting ranges to make sure that even for the brightest days we had only limited saturation of pixels in both bands (over-exposure). This analysis led us to fix the aperture on both cameras to f=11 and the time exposure to 1/160 s for the RGB camera and 1/40 s for the NIR camera. Images with significant light limitations were discarded based on their RGB histograms below set thresholds. These were images with usually very low visibility on rainy days or presence of haze/mist or low lying cloud cover, and VIs computed on them would contain large uncertainty.

The image processing requires several steps: (1) the two concurrent images from both cameras were registered to each other with a cross-correlation algorithm which searches for the shift in horizontal and vertical directions to obtain the best pixel-based fit; (2) the vegetation indices VIs were then computed on the registered images; and (3) the VI images were orthorectified with the method described in our paper to obtain VI maps overlain on the floodplain surface. We agree with Referee 1 (C740) that this last step is not strictly necessary for the statistical analysis of vegetation change; however our goal in ongoing research is to look at the relations of vegetation response to floods with respect to floodplain location. For this step we are using a high resolution DEM of the floodplain and a 2-D hydrodynamic model to simulate flooding frequency for different discharges and we need to know exactly where individual plants are located to quantify their flooding-related stress. The results of this study will be presented in a subsequent paper (see also request of Referee 3, C1379).

In our analysis of pre- and post-flood changes we chose to take the median pixel value of change in images within k days of the flood. In response to Referee 3 (C1379) our justification of this is: (a) we want to ensure that we have an “immediate” response, i.e. changes in vegetation are related to the flood forcing (erosion, deposition) and floodplain inundation (wetting) and not to longer term post-flood groundwater variability and floodplain drying; and (b) within this window we want to get a robust statistic given the variability between days in terms of light conditions following a storm, which we think is guaranteed better by the median than taking e.g. an arithmetic mean. It is indeed true, as the Referee points out, that the images after a flood peak may still be affected by the flood recession. However most floods we observed had recessions less than 24 hrs long, so this effect is not likely to persist for more than 1-2 days (images) and these will not affect the pixel-based median of the estimated vegetation change. Connected to this is the question of Referee 3 (C1379) how we can “discriminate between vegetation enhancement as a response for bigger and mature trees”. We do this only on the basis of the change being conditional on pre-flood VI (see Figure 3 in the manuscript). This means that we are assuming that high values of VI correspond to bigger and mature trees. On the basis of our qualitative assessment (e.g. see blue area in Figure 4 of our manuscript), we are confident that these are indeed larger trees on the highest part of the gravel bar. We will do ground measurements of canopy height in the future to validate this.

5. Unmanned Aerial Systems (UAS)

The point was raised that small Unmanned Aerial Systems (UAS) would be “more appropriate for this kind of work and that we need to convince the readers that ground-based photography is superior to aerial and UAS photography for this type of research (Referee 1, C738)”. We did in fact omit the UAS as an independent remote sensing image collection alternative and we will add citations and examples of these applications in the revised manuscript (e.g., Berni et al., 2009; Dunford et al., 2009; Zarco-Tejada et al., 2009). Thank you for pointing that out to us.

However, we would like to make it clear that we do not see ground-based photography as a competitor to aerial and UAS photography and the question to us is not which one of these is superior. Clearly all have advantages and disadvantages, which we will attempt to clarify better in the revised manuscript. The main advantage of ground-based photography by fully automatic systems such as ours is that there are practically no running costs after installation. Checking the cameras, replacing the batteries, and downloading the data requires few trips to the camera location, while every UAS deployment, not to speak of devoted aerial photography, would be connected with substantial commitment in time and planning (and finances). Since one of our goals is to quantify short-term floodplain change it is imperative that we have continuous data shortly before and immediately after large flood events, which is possible only with automatic image collection systems because of the inherent climatic unpredictability of these events. Of course the main advantage of UAS is vertical photography, the possibility to carry different types of thermal and narrowband multispectral sensors, and an even higher spatial resolution, which allows a more spatially consistent assessment of floodplain surface properties.

Our vision is that for the problem described in our paper, the best solution could be to use ground-based such as ours photography for permanent monitoring of the floodplain, combined with occasional UAS and aerial photography for periodic high quality images, possibly with simultaneous ground field measurements of spectral reflectance (and other biomass characteristics) for calibration and validation of vegetation indices. This is the vision we would like to transmit with our paper.

6. Ecological implications

Several questions were raised about ecological implications of our research, e.g. “how monitoring short-term vegetation change can inform science and management of riverine systems, and [provide] more ecological information about the post-flood vegetation dynamics" (Referee 1, C738, C740).

Alpine rivers are highly dynamic systems, which offer a limited amount of ecological functions to support riparian vegetation. Namely, the coarse sediment in gravel-bed braided rivers is a difficult surface for vegetation establishment, frequent inundation causes habitat turnover, and the local microclimate on gravel bars may be extreme (e.g. Karrenberg et al., 2002). In addition to natural constraints, riparian vegetation often needs to deal with human-induced alternations, such as flow regulation due to hydropower operation affecting both low flows and floods. Floods in particular play a key morphological and habitat turnover role.

While vegetation stress caused by water scarcity is well covered in the scientific literature (e.g. Aroca, 2012), vegetation stress due to the water excess is discussed considerably less (e.g. Lichtenthaler, 1996; Lambers et al., 2008). Nevertheless, it is generally acknowledged that plants may adjust to extreme conditions if they can survive them (e.g., Molinier et al., 2006; Bruce et al., 2007). For instance, plant stress due to water excess by floods or an increased water table can cause both physiological and morphological responses of vegetation (Hatfield, 1997; Kozlowski et al., 2002) such as root mortality or decrease in photosynthetic activity, plant growth, dry matter production, and reproduction. Thus, applied stress on vegetation can have short-term as well as long-lasting effects on the riverine ecosystem, which should be studied and evaluated.

The short and long-term consequences of vegetation stress in our study have an informative value for the science and management of riverine systems. Namely, the identification of zones with prospering vegetation or with vegetation under constant stress is a valuable indicator of ecological conditions and morphological stability of the river system. Furthermore, the spatial distribution and temporal dynamics of vegetation stress are important attributes for the evaluation of the ecological sustainability of river

regulation and restoration projects. Moreover, from the theoretical point of view, our results help to better understand the complexity of riparian zone organization from the spatial perspective and, if combined with additional field measurements, this may be the basis for developing predictive models.

Referee 1 (C741) raised the question "by which mechanisms floods can enhance vegetation vigor at such short time scales; is it possible that light availability might increase after a flood clears some overstory? access to nutrients changes?". This is in fact an interesting and open question. We are convinced that the vegetation enhancement we see in our data is most likely only marginally due to increased light availability after floods. Floods rarely erode mature trees which could be shadowing understory. It appears to us that wetting the gravel bar during several hours of inundation in combination with an increased water table after floods is a key process which leads to more water availability for established plants across the gravel bar. This is the process we explain in our manuscript and will stress in the revision. The question of nutrient limitation which Referee 1 raised is indeed an important one and in fact we have started sampling leaves for N/P analysis precisely to address this question and find out if our floodplain system is exhibiting signs of N or P limitation. We plan to pursue these questions in our future research, but for the present manuscript we do not have enough solid data to make additional conclusive statements on these processes.

A summary statement on the ecological significance of our research is that monitoring systems such as ours is critical for the understanding of the adaptability of floodplain riparian systems to a changing flow regime and microclimatic extremes in nutrient limited environments at a short time scale. This is important from ecological as well as river management viewpoints because it allows us to address the vulnerability of riparian systems and their potential response to change.

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Figure Captions

Fig 1: Typical surfaces which are within the images of the studied floodplain. From left: gravel bar detail with small herbaceous plants and taller 1-3 yr salix saplings; 2-3 m tall salix trees which range up to 5-6 yrs in age; and tall salix, poplar and alder trees which can be up to 20 yrs in age. Flood debris is visible at the stems of larger trees.

Fig 2: Spatial detail of the upstream section of the study reach with predicted vegetation scour (non-transparent/transparent red color) after the flood in July 2011 shown together with the actual distribution of vegetation on the surface: A) full view of the study reach with estimated vegetation scour, B) detail of pre-flood distribution of vegetation, image from 11/7/2011, C) detail of post-flood distribution of vegetation, image from 22/7/2011.

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Fig. 1. Typical surfaces within the images of the studied floodplain. For detailed caption see end of response text.

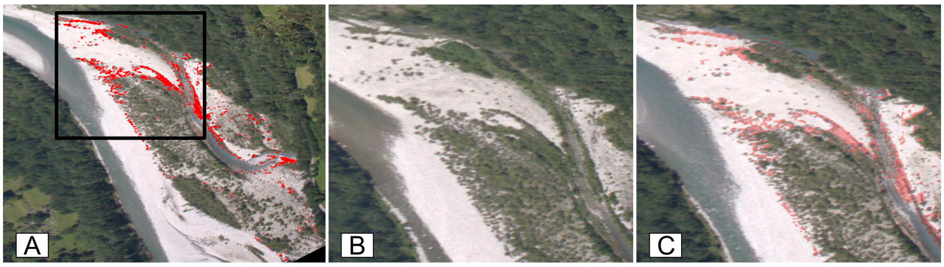

Fig. 2. Spatial detail of the upstream section of the study reach with predicted vegetation scour. For detailed caption see end of response text.