Testing the influence of topography and material properties on catchment scale soil moisture patterns using remotely sensed vegetation patterns in a humid temperate catchment, northern Britain

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Abstract

In order to evaluate the relationship between the apparent complexity of hillslope soil moisture and the emergent patterns of catchment hydrological behaviour and water quality we need fine resolution catchment-wide data on soil moisture characteristics. This study proposes a methodology whereby vegetation patterns obtained from high-resolution orthorectified aerial photographs are used as an indicator of soil moisture characteristics. This enables us to examine a set of hypotheses regarding what drives the spatial patterns of soil moisture at the catchment-scale (material properties or topography). We find that: the pattern of *Juncus effusus* vegetation is controlled largely by topography and mediated by the catchment's material properties. Characterising topography using the topographic index adds value to the soil moisture predictions relative to slope or upslope contributing area (UCA). However, these predictions depart from the observed soil moisture patterns at very steep slopes or low UCAs.

Key words: soil moisture, vegetation, remote sensing, catchment scale, depth to water table

Introduction

Detailed process research at the hillslope scale (e.g. Freer *et al.*, 2002) indicates that small scale spatial variability is important in driving hydrological processes; yet at the catchment scale consistent statistical patterns emerge that can be characterised and reproduced through simple indices (e.g. Rodriguez Iturbe *et al.*, 1995; Lane *et al.*, 2009). Understanding the spatial patterns of soil moisture at the catchment-scale is important: 1) because water is the vector that moves material, pollutants and pathogens across the landscape (Kay and Falconer, 2008); 2) because water is one of the key drivers in biological, chemical and physical surface processes from species growth to mass wasting to sediment transport (Skopp *et al.*, 1990; Sierra, 1997; Iverson *et al.*, 1997; Ridolfi *et al.*, 2000; Gabet *et al.*, 2006); and 3) in order to understand the potential impacts of spatially discrete interventions to manage water flux (e.g. blocking drainage ditches or changing landuse; Ramchunder *et al.*, 2009; Odoni and Lane, 2010). This poses a fundamental question: does the variability revealed in plot-scale measurements constitute a key signal that needs to be accounted for explicitly; or simply noise in a larger scale spatial signal that can be adequately characterised at the catchment scale?

Several explanations have been forwarded for the emergent soil moisture patterns at a catchment scale; most notably that they are driven by topography, often characterised by the topographic index (Kirkby, 1975; Lane *et al.*, 2009); or that they reflect the pattern of one of the underlying key driving variables. In some cases these patterns are fractal (Rodriguez Iturbe *et al.*, 1995; Pelletier *et al.*, 1997), in others they have been related to soil or rock type (Boorman *et al.*, 1995; Onda *et al.*, 2006). These explanations are likely to vary depending on the dominant hydrological processes in a location and therefore on its climatic and topographic properties (Tetzlaff *et al.*, 2008). But even for the upland humid temperate environment on which we will focus in this study there remains a range of possible explanations. These are testable but they require spatially distributed soil moisture information at a resolution fine enough to pick up the variability visible from hillslope studies and over areas large enough to identify emergent patterns. Although soil moisture dynamics through time can be measured reliably using point instrumentation (e.g. Lamb *et al.*, 1998), the expense of such instrumentation is generally prohibitive for consideration of catchments any larger than a few km^2. Spatially extensive surveys are possible but are not necessarily of use if they provide data at discrete time periods given the established variability of soil moisture in relation to rainfall events. In this paper we show the potential of using vegetation as a diagnostic indicator of spatially-distributed time-averaged soil moisture and use it to test two independent but compatible hypotheses on what generates spatial soil moisture patterns in humid temperate environments. Our hypotheses are: H1) that the spatial pattern of *Juncus effusus* which is an indicator of soil moisture regime in our study area is driven by topographic properties; and H2) that the pattern is driven by material properties that we can characterise from the soil and rock type. Implicit in the first hypothesis is the subhypothesis that the best way to characterise these topographic properties will be the topographic index (Kirkby, 1975). These hypotheses have important implications for our ability to model spatial soil moisture patterns since models tend to be driven by topography or in some cases topography with soil or rock properties.

Defining and characterising soil moisture regime

The complexity of soil moisture means that measurement methods that enhance our ability to capture its spatial dynamics are highly sought after. There remains a gap in our ability to routinely measure soil moisture at intermediate (10^3-10^{-1} km^2) scales (Robinson *et al.*, 2008). Direct, time-dependent measurements are costly and time consuming and cannot feasibly be taken over areas large enough to capture emergent patterns. Research into remote sensing of soil moisture has focussed largely on data from satellites and has made considerable progress, enabling generation of regional soil moisture datasets (Wigneron *et al.*, 2003; Kerr, 2007). However, these datasets only measure soil moisture in the top few centimetres of the soil, are commonly instantaneous and have a resolution that is too coarse (>3600 m^2) to capture the small-scale variability in soil moisture. Thus, new sources of spatially distributed information on soil moisture at fine resolution (<100 m^2) and over areas large enough (>10 km^2) to identify emergent patterns are essential to the progress of hydrological research.

The presence of some vegetation species has been connected to certain soil moisture conditions (Gowing and Youngs, 1997; Araya *et al.*, 2010). The performance of plant species is based on their ecological niche - the conditions (in terms of distribution of resources) under which species can survive or thrive. The resources that define a plant's ecological niche include nutrients, light and soil moisture. Where the limiting factor is either: too little available water or too much (limiting root respiration), the pattern of vegetation can be used as an indicator of the soil moisture regime. This differs from other soil moisture measurements since vegetation is sensitive to both the volumetric soil moisture and the soil water potential and to both the intensity *and* duration of events (floods or droughts), providing a time integrated measurement. For example, a plant's ecological niche might be defined in terms of a number of days per year that the water table exceeds a given depth (Gowing and Youngs, 1997).

Soil moisture has been shown to be very important in defining the niche of many plant species in lowland grasslands (*e.g.* Silvertown *et al.*, 1999; Araya *et al.*, 2010) and although the ecological niche of many upland plant species is yet to be defined, indicator values such as Ellenberg values (Ellenberg, 1979; Hill *et al.*, 1999) can be used to determine hydrological conditions from the plant species present. Ellenberg indicator values are based on the realised niche of plant species *i.e.* the niche they occupy as a result of competition from other plant species. Ellenberg F values (from the German *feuchtigkeit*) define moisture requirements of plants on a scale of one to twelve from indicators of extreme dryness (Ellenberg F value 1) though to submerged plants (Ellenberg F value 12). It is important to note that the presence of a species can indicate a particular moisture regime (defined by its niche), but its absence does not rule out the presence of that regime. Therefore, a vegetation species can be used for large scale fine resolution mapping of soil moisture regimes but will capture a subsample of areas within that regime.

Despite the potential use of plants in determining hydrological conditions they are rarely used as indicators by hydrologists. Where they have been used there has been good agreement with soil moisture measurements (Wang, 2000). However, species identification has been through direct field survey, limiting the spatial extent of its application (Klinka *et al.*, 1989). Remote sensing can be successfully used to identify vegetation species (Yu *et al.*, 2006; Mills *et al.*, 2006) but this capability has rarely been used to characterise the soil moisture regime that they indicate. An opportunity exists to link these techniques by developing a method of soil moisture characterisation using aerial colour imagery to identify indicator vegetation species. Such a method has considerable potential since high resolution aerial imagery is widely available in many countries at an ever increasing resolution and decreasing cost. This study focuses on data collected from airborne platforms since these are the only available data suitable to identify vegetation and resolve spatial soil moisture patterns at a resolution sufficient to characterise its fine scale spatial variability.

What drives spatial soil moisture patterns in humid temperate environments?

The dynamic source area concept (Hewlett and Hibbert, 1967; Ragan, 1968) and a realisation of the importance of shallow subsurface flow in humid temperate environments (Hursh, 1936; Hewlett and Hibbert, 1967) led to numerous studies on the relations between topography, subsurface flow convergence and runoff generation (Dunne, 1970; Anderson and Burt, 1978). They found that 1) where the topographic gradient (β) is shallow, flow will be slower and the ground wetter; 2) where flow lines converge in hillslope hollows the upslope contributing area (a) will be larger, as will the volume of water flowing through that point and as a result the ground will be wetter. These were represented by Kirkby (1975) in the topographic wetness index (TWI):

Equation 1

$$TWI = \ln\left(\frac{a}{\tan\beta}\right)$$

Hillslope scale experiments have supported and developed these theories (Montgomery *et al.,* 1997) whilst others have compared spatial predictions of models (or patterns of TWI) with distributed measurements. These measurements have included: soil moisture in the upper soil profile (e.g. Western *et al.*, 1999), depth to the water table in wells and piezometers (e.g. Jordan, 1994), or the spatial pattern of saturation during a rainfall event (e.g. Blazkova *et al.*, 2002). Many of the studies have demonstrated similarities in predicted and observed saturated areas, and patterns of the TWI (e.g. Beven and Kirkby, 1979; Blazkova *et al.,* 2002). However, the level of agreement is variable ranging from: good, with some points of departure; to poor (e.g. Ambroise *et al.*, 1996), with local conditions (sub-grid topographic features, local soil characteristics and non-topographic flow pathways) exerting at least as important a control on saturation.

In fact, since the discovery of lateral subsurface flow and topographic control on soil moisture, further hillslope studies have revealed significant complexity and heterogeneity in hillslope responses to rainfall (Bouma *et al.*, 1977; Freer *et al.,* 2002; Uchida *et al.*, 2005; Tromp-van Meerveld and McDonnell, 2006; Hopp and McDonnell, 2009). Much of this heterogeneity can be assigned to differences in the soil material properties in the catchment controlling a location's capacity to hold water (e.g. soil depth, porosity, soil water characteristics) and the speed with which water is transferred through it (e.g. vertical and lateral hydraulic conductivity of both matrix and macropores / fractures).

If we could capture these material properties (e.g. by relating them to soil type or geology) we might be able to explain the heterogeneity. However, these material properties are often spatially heterogeneous, within a particular soil type, and recent research has demonstrated the importance of: non-uniform soil depth (Freer *et al.,* 2002; Tromp-van Meerveld and McDonnell, 2006);

preferential flow through bedrock (Montgomery *et al.*, 1997; 2002), soil pipes and macropores (Bouma *et al.*, 1977; Hutchinson and Moore, 2000; Uchida *et al.*, 2005). Further, the material properties are commonly poorly-constrained between soil types or geologies and the soil type and geology data itself is limited in its detail, resolution and crucially spatial extent. Thus, critical to hydrological generalisation is knowing when simpler assumptions (such as those made when calculating the topographic index) apply, both in general for a given catchment and in particular for certain areas of a given catchment. One indictator is the presence of wetter patches (as revealed by *J. effusus*) in zones that are predicted to be drier. We can use this unexplained variability to test our hypotheses and identify other sources of variability in spatial soil moisture (e.g. Wilson *et al.*, 2004).

Methodology

Study Site

We focus on the Newlands Valley in the English Lake District because it is an upland catchment in a humid temperate environment where: 1) the relatively steep topographic and hydraulic gradients should favour a strong topographic influence on spatial soil moisture; and 2) subsurface flow and saturation excess overland flow should make the assumptions of variable source area hydrology reasonable. The climate of the study area is humid temperate. Average annual rainfall ranges from 1600 mm a^{-1} in the valley bottoms to 3000 mm a^{-1} on the peaks with a spatial average of 2400 mm a^{-1}. The wettest months are October through January and the driest are March through June, but the valley bottoms show little difference in rainfall between months. Fog is common at any time of year, and the study area averages ~2.5 hours of sunshine per day. Monthly average temperatures in the valley bottom (at 70 m) range from 3°C (January) to 15°C (July) and decrease with altitude at a lapse rate of 1°C per 150 m. Temperature oscillates about freezing point for long periods of every winter resulting in a high frequency of oscillations between rain, sleet and snow. Normally, significant snow fall only occurs between November and April, and valley bottoms typically experience 20 days snow fall, 200 wet days, and 145 dry days.

The scope of study was limited to the unenclosed upland areas, grazed by sheep with a density ~2 sheep per hectare (MAFF, 1998) but not managed with any fertiliser or pesticide (Figure 1). The more intensively managed lowlands were excluded because the strong human influence on land management in these areas would render them unsuitable for wetness classification from natural vegetation. Forest areas (which are predominantly conifer plantations) were also excluded because they mask the understory vegetation making classification from aerial photographs difficult. As a result our conclusions are limited to unforested upland areas. The Newlands Valley is a subcatchment of the Bassenthwaite catchment (347 km^2), Lake District National Park, UK. The study area is 38 km^2 with an elevation range from 70 m above sea level where the river flows in to

Bassenthwaite Lake, to 839 m on the divide close to Crag Hill. The catchment land cover is a patchwork of bare rock, acid grass, rough grass, heath and moorland (CEH 2000).

<Figure 1 near here>

Vegetation in the study area is dominated by *Agrostis-Fescue* grasslands, defined in the British National Vegetation Classification (NVC) as U4 *Festuca ovina-Agrostis capilaris-Galium saxatile* grassland (Rodwell, 1992). It is a grassland typical of upland hillslopes such as those found in the Lake District, dominated by grasses with several forb, rush and sedge species and occasional dwarf shrubs including heather and bilberry. Within this grassland matrix are areas with a greater abundance of bracken (U20 *Pteridium aquilinum-Galium saxatile* community; Rodwell, 1992) and wetter areas of rush pasture dominated by soft rush (M23 *Juncus effusus/acutiflorus-Galium palustre rush pasture*; Rodwell, 1991). In these areas species typical of wet habitats such as golden saxifrage (*Chrysosplenuim oppositifolium*) and the mosses *Hylocomium armoricum* and *Cinclidotus fontaloides*, can also be found. Further up the slope heather (*Calluna vulgaris*) dominates the vegetation and heathland becomes established.

The solid geology of the area is entirely made up of Lower Palaeozoic Skiddaw Group rocks (Cooper *et al.*, 2003), the two dominant geologies: the Buttermere and Kirk Stile Formations differ very little in terms of their properties since both are composed largely of siltstone and mudstone (Woodhall, 2000; Figure 2a). Both formations have relatively low permeability and we would not expect a significant difference in soil moisture in their overlying soils (Freeze and Cherry, 1979). The Newlands valley is largely unforested and has a strong glacial legacy both in terms of valley form (trough shaped valleys with planar valley sides) and material properties with many drift-mantled slopes (Figure 2b). The surficial geology is made up of alluvial deposits and fans, talus (slope deposits) and till (glacial deposits). Whilst these broad classes are likely to encompass a very wide range of properties we might expect that the talus and alluvial deposits would be high conductivity (and therefore drier) while till would be low conductivity (and therefore wetter). The soils in the catchment have been mapped as three units based on the revised (2001) 1:250,000 national soil map derived from Soil Survey Staff (1983). The valley bottoms are covered with slowly permeable seasonally waterlogged loam soils (Brickfield unit) whilst the slopes have a mix of deeper (~0.7 m) well-drained loam soils (Manod unit) and very shallow (~0.2 m) very acid peat soils with low permeability and little available storage capacity (Skiddaw unit; Figure 2d). We would expect the lower capacity peat soils to be wettest and most responsive and the deeper more permeable well-drained loam soils to be driest and least responsive; the waterlogged loam soils in the valley bottoms should also be wet since although they are deep they are lower conductivity and often have a shallow impermeable layer in the soil profile (~0.34 m).

<Figure 2 near here>

Juncus as an indicator of soil moisture regime

Juncus sp. have been selected for this study because they are recognised within the ecological literature as indicators of soils which are constantly moist or damp (Hill *et al.*, 1999). *Juncus effusus* (soft rush), the dominant *Juncus* species in the study area, is commonly found on the banks of water bodies, springs and flushes. It can grow in shallow standing water but is most commonly found on damp soils, especially those subjected to winter flooding, and soils with a variable water table (Sinker *et al.*, 1991). This is reflected in its Ellenberg F value for soil moisture, which is 7 (Table 1). As competitive species (Grime *et al.*, 2007), in wet conditions, *Juncus* sp. are frequently dominant (Ervin and Wetzel, 2002). However, although all areas with *J. effusus* growing in them are wet, not all wet zones will be dominated by *J. effusus*. Other reasons such as nutrient status, soil pH and light level may make conditions unsuitable. The impact of these other controls should be relatively small in our study area; *J. effusus* is not limited by elevation over the range of altitudes found in the study area and is tolerant of the pH range typical of the region (Table 1). *J. effusus* stems are bright or dark green, tall and stiffly erect, growing in dense tufts. It is particularly visible on aerial imagery due to not only a change in colour but also in texture, growing in tufts, which remain distinct, not forming continuous stands (Richards and Clapham, 1941). Additionally *Pteridium aquilinum* (bracken); and *Calluna vulgaris* (heather), other dominant species in the region, are good indicators of drier conditions (with Ellenberg F values of 5 and 6 respectively; Table 1), and are clearly distinguishable on the aerial imagery, minimising the risk of miss-classification in these areas.

<Table 1, Figure 3 and Figure 4 near here>

To test the relationship between *J. effusus* and soil moisture in the study area we collected water table measurements at 95 wells within a nested sampling network over a 500 m by 500 m hillslope (labelled A on Figure 1). The minimum water table depth in each well was measured over two four month periods: from November 2006 to February 2007 and from February 2007 to May 2007. For the first period monthly total precipitation ranged from 85 to 337 mm with a mean of 241 mm; estimated monthly total PET (following Thornthwaite, 1948) ranged from 14 to 28 mm with a mean of 19 mm. For the second period monthly total precipitation ranged from 44 to 101 mm with a mean of 79 mm; estimated monthly total PET ranged from 14 to 65 mm with a mean of 37 mm. The results show that in *J. effusus* covered areas water tables are closer to the surface both in absolute terms (Figure 3a) and relative to soil depth (Figure 3b). Plotting these data as exceedance probabilities shows that water table depth is consistently biased in the presence of *J. effusus* (Figure 4a) so that *J. effusus* covered sites have a much higher probability of water tables shallower than 0.25 m (0.5) relative to the full sample (0.1). We compare the water table exceedance probability at *J. effusus* sites with that for the full sample to show the extent to which the *J. effusus* sites differ from the general landscape behaviour and because these are the two components used in the calculation of the conditional probability of *J. effusus (i.e.* $P(j \mid x) = P(j \cap x) / P(x)$; where x is minimum water table depth and j is *Juncus effusus*). Figure 4b shows the conditional probability of finding *J. effusus* (CPJ) at a location with a given water table depth. Since the conditional probability is influenced by the bin size over which it is calculated we quantify this uncertainty by calculating the mean and standard deviation of conditional probabilities from 20 different bin widths ranging from 1.5 to 0.1 m (i.e. from 2 – 21 bins). The conditional probability plot (Figure 4b) shows that sites with water tables deeper than 0.5 m have a low CPJ while the probability rises very sharply for sites with minimum water tables shallower than 0.5 m. This supports the hypothesised relationship between *J. effusus* and water table depth (indicative of wet soil moisture regime) but suggests that while areas with *J. effusus* are very likely to have shallow water tables other controls on vegetation niche mean that there will be some locations with shallow water tables but without *J. effusus*.

Aerial Imagery: acquisition and analysis

True vertical aerial photographs for the Newlands Valley study site were collected in July 2005 with a Zeiss LMK metric camera at an altitude of 1,500 m with a photo scale of 1:10,000 and pixel resolution of ~0.1 m. Thirty of these images covering an area of ~100 km^2 were orthorectified by direct linear transformation (El-Aziz and Karara, 1978) in ERDAS IMAGINE. Ground control points were collected from features identifiable on Ordnance Survey 1:25,000 scale maps that were clearly visible in the images. Camera orientation was established with a Root Mean Square Error (RMSE) of <2 m. The images were orthorectified using elevation data collected using airbourne Interferrometric Synthetic Aperture Radar with a resolution of 5 m and vertical precision of ~0.5 m. Orthorectifed images were generated by resampling the original images into the new coordinate space at 0.1 m resolution using bilinear interpolation. The resultant images have planimetric errors <3 m and pixel sizes ~0.1 m, they overlapped by ~60 % in an east / west direction and ~30 % in a north / south direction. Because the photographs were to be used for manual vegetation identification there was no need for radiometric correction (which would inevitably result in some information loss). Our ability to map *J. effusus* from the aerial images was verified at the study hillslope (A in Figure 1) where planimetric mapping errors were dominated by the orthorectification error and remained small (~2 m) relative to the resolution of the elevation data. The mapped limits to *J. effusus* zones are necessarily crisp where the true boundaries are sometimes more diffuse introducing some potential variability. To maximise consistency in boundary definition all *J. effusus* zones were mapped by a single person over a 3 day period. *J. effusus* covered 4 % of the study area.

<Figure 5 near here>

Analysis to test hypotheses

For H1 we test two topographic variables that we identified as important in defining soil moisture: slope and upslope contributing area (UCA) and their combination as the topographic wetness index (TWI) for hydrologically similar zones (Equation 1; Kirkby, 1975). Although other topographic variables could be used, here we focus on these three frequently used variables that most simply represent the processes we expect to dominate in our humid temperate study area (Figure 6). We derive topographic variables from the IfSAR elevation data using the Digital Surface Model (DSM), which includes the vegetation in its elevation prediction. However, in our study area where vegetation is generally <1 m tall and there are very few cultural features such as buildings, the error introduced by taking the first return is generally smaller than that introduced by filtering the data to produce a 'bare earth' model (Milledge *et al.*, 2009). We calculate slope using the Zevenbergen and Thorne (1987) algorithm; UCA using the infinite directions (D∞) algorithm (Tarboton, 1997) after filling sinks using the Planchon and Darboux (2002) method; and TWI using equation 1. To address H2 we test three sets of catchment material properties: Solid geology, surficial or drift geology, and soil type (Figure 2). We use solid and surficial geology information from the digitised BGS 1:50,000 Geology map (sheet EW029) and soil information from the National Soil Research Institute 1:250,000 digital Soil Survey Map. In each case we extract the topographic or material properties for the full study area and for each (25 m^2) cell tagged as wet and compare them as discussed below.

To address our two hypotheses we assume that *J. effusus* is indicative of a 'wet' soil moisture regime and assess the impact of first topography then material properties on the distribution of *J. effusus*. Focussing first on the topographic signal, we qualitatively assess the influence of slope and UCA based on the degree to which *J. effusus patches* cluster in slope area space. We compare the probability distributions of slope, UCA and TWI for *J. effusus* patches with those for the full study area to examine the conditional probability of finding *J. effusus* (CPJ) with each. Note that as above we compare the *J. effusus* subset with the full set (rather than the non *J. effusus* subset) because this is the comparison used in the definition of the conditional probability. We then calculate the probability of finding *J. effusus* conditional on both slope and UCA to understand the influence of these two variables in combination on the CPJ. Finally, we assess the impact of material properties on *J. effusus* patterns, with and without controlling for the co-variance between material properties and topography.

Results

Topography

We have hypothesised (H1) that a cell's soil moisture regime, and therefore the presence of *J. effusus,* is related to its topography in terms of slope and UCA. By discretizing the study area into a grid of cells (25 m^2), extracting the local slope and UCA for each of these cells (Figure 6a and c), and plotting them against one another (Figure 7a) we can visualise the relationship between these two properties for every cell in the study area. The light green point cloud in Figure 7a defines the combinations of slope and UCA that are found within the study area, the density of the points gives a qualitative indication of the frequency with which cells of a given slope and UCA are found. Plots of the same kind have been used to define geomorphic process domains (Montgomery and Foufoula-Georgio, 1993; Ijjasz Vasquez and Bras, 1995) such as the transition from hillslope to channel processes (Stock and Dietrich, 2003).

<Figure 6 near here>

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They are also a convenient method of visualising the distribution of *J. effusus patches* in relation to two of the driving topographic variables (slope and UCA). Cells that contain *J. effusus* are plotted in dark blue (Figure 7a) over the results from the full study area in light green. They show that *J. effusus* patches, which make up 4 % of the study area, are not independent of slope or UCA nor do they follow a clear trend; instead they cluster at UCAs between 500 and 5000 m^2 and slopes between 0.1 and 0.6 m/m (6–31°). The location of the cluster represents limits to the topographic settings in which *J. effusus* out-competes other species. There is a clear upper limit to the slopes at which this occurs, with *J. effusus rarely found* on slopes steeper than 1 m/m (45°). The lower UCA limits are less clear, with *J. effusus* even in cells with contributing areas of only 25 m^2 (a single cell). Whilst this is likely to be an artefact of fine scale topographic roughness, it makes identifying a lower UCA limit for *J. effusus* difficult. The upper UCA and lower slope limits to the cluster of *J. effusus* cells are defined more by a reduction in the number of cells with these properties than by a reduction in the proportion of these that have *J. effusus*. This is important, because our definition of the topographic conditions that favour *J. effusus*, should not preference common areas of the landscape over rarer ones, we address this in the next step of our analysis.

Figure 7b shows the probability distributions for slope, UCA and TWI for both the full study area (dashed green) and *J. effusus patches* (blue). By comparing these probability distributions we can calculate the conditional probability of *J. effusus (CPJ*; Figure 7c). This can be interpreted as the probability that a cell with a given property (local slope, UCA or TWI) will have *J. effusus* in it, removing the preference towards common areas in our analysis. Since the conditional probability is influenced by the bin size over which it is calculated we quantify this uncertainty by calculating the mean and standard deviation of conditional probabilities from 60 different bin widths ranging from 6 – 66 bins.

The distribution of TWI values for *J. effusus patches* is very similar to that for the full study area up to ~3.5 (Figure 7b). At this point, there is an offset in the curves, which is maintained over the rest of the range. As a result the CPJ has a small peak (~0.03) at TWI ~3.5 (Figure 7c) followed by a second much larger peak (~0.24 at TWI ~9.5), which is likely to reflect a topographic control on *J. effusus* on the left tail (TWI 6–9.5) and a movement from hillslopes to unvegetated channels on the right tail (TWI 9.5–12). The slope distribution for *J. effusus* patches is tighter and skewed towards lower slopes, than the full study area, with much lower mean, mode and median (Figure 7b). The CPJ at a given slope reflects this, with relatively high (~0.15) CPJ for slopes shallower than 0.5 m/m (27°), then a rapid decline to a very low (<0.01) CPJ for slopes steeper than 0.7 m/m (Figure 7c). The UCA distributions show a decline in probability with increasing UCA for both *J. effusus* patches and the full study area (Figure 7b). The distributions are offset so that the full study area has a higher probability of low UCAs and declines more rapidly. Whereas *J. effusus* patches have a lower probability of low UCAs and a longer heavier tail to their distribution (Figure 7b). These differences are reflected in the relationship between CPJ and UCA which is initially high due to noise in the topographic data, then low for UCAs between 10^2 and 10^3 m^2, before rising to a peak at ~10^4 m^2 (Figure 7c). At this point ~20 % of cells with UCAs of 10^4 m^2 contain *J. effusus* (i.e. CPJ = 0.2). The probability of *J. effusus* patches at higher UCAs declines slightly, probably reflecting the shift from hillslope to channel cells (where *J. effusus* is no longer viable due to lack of soil). We limit the x-axis to 10^5 m^2 beyond which, the very limited data causes the signal to become noisy as it reacts to individual *J. effusus* covered cells. The peak CPJ for cells with a given set of UCA values is 0.2 while that for a given set of slopes is 0.15. This difference is significant given the uncertainty related to bin sizes (p<0.001, using a two sample t-test) suggesting that UCA exerts a stronger control on *J. effusus* location than slope. However, both slope and UCA have peak CPJs that are significantly lower (p<0.001) than that for TWI (0.24), reflecting the importance of the two variables in combination, since in isolation their effects can offset each other.

The TWI is only one hypothesised form of the relationship between slope, UCA and soil moisture regime. By looking at CPJ in two dimensions (slope area space) we can assess the impact of slope and UCA in combination without assuming the form of the relationship *a priori*. We calculate CPJ over a regular grid by searching for the nearest 1000 points to each grid node, defined geometrically (i.e. in log-log space), then counting the proportion of these points that contain *J. effusus*.

Accounting for the relative density of *J. effusus* cells in relation to dry cells (Figure 7d) produces a very different picture of the relationship between topography and CPJ compared to that in Figure 7a. There is a clear maximum probability (> 0.34) between 9,000 and 15,000 m^2 UCA and 0.1 and 0.15 m/m (7–10°). There is a band of 0 probability at slopes greater than 0.7 m/m (35°) suggesting that slopes steeper than this do not sustain *J. effusus* independent of their UCA. For slopes between 0.2 and 0.7 m/m (11–35°) probabilities increase rapidly with decreasing slope. The influence of, slope dominates that of UCA and is considerably stronger than predicted by the TWI (dashed contours in Figure 7d). At slopes lower than 0.2 m/m (11°) slope exerts a limited control on the CPJ; in areas where the UCA is also low (< 3,000 m^2) neither variable exerts a strong control on CPJ. For UCAs > 3,000 m^2 CPJ has an increasingly strong dependence on UCA up to the maximum likelihood at 10,000 m^2. In areas with low slopes (<0.1 m/m) and high UCAs (>15,000 m^2) the probability is lower probably due to sparse available data in these zones (Figure 7a) and the fact that many of these cells are channels. If the TWI were a perfect predictor of CPJ we would expect the probability surface to follow the TWI contours. Although the broad trends from high probability at high TWIs and low probability at low TWIs are consistent the form of the predicted and observed relationships in slope area space differs (Figure 7d).

Material Properties

Figue 2 shows the distribution of mapped *J. effusus* patches in relation to maps of the Newlands Valley study area showing solid geology, surficial geology and soil type (Figure 2). The spatial pattern of *J. effusus* patches does not appear to be related to solid geology (Figure 2a) and there is little difference in the CPJ on the dominant Buttermere and Kirk Stile formations (4.6 and 3.9 % respectively, Table 2). *J. effusus* tends to occur predominantly in certain types of surficial geology (Figure 2b and Table 2) particularly alluvium, alluvial fan deposits and glacial till. These three deposits make up only 20 % of the catchment but contain 76 % of the *J. effusus* (Table 2) and have CPJs of 0.45, 0.17 and 0.14 respectively. However, since these deposits all tend to occur predominantly towards the valley bottoms this relationship may be the result of the co-variation of CPJ and material properties with topographic form. Figure 2d and Table 2 suggest that hilltop peat soils have the lowest CPJ (0.02), well-drained loam soils have a higher probability (0.05) and waterlogged loam soils in the valley bottoms the highest probability (0.25).

< Table 2 near here>

Two questions arise from this co-variation between topography and material properties. First, what is the influence of material properties on CPJ independent of topography? Second, what is the influence of material properties on the relationship between CPJ and topography? To address these, we can analyse the relationship between CPJ and material properties controlling for topographic influence by comparing CPJs for areas with different material properties but with the same TWI (Figure 8). The resultant plots (Figure 8a-c) are complex with the material properties and TWI interacting in their control on the probability of finding *J. effusus*.

<Figure 8 near here>

To address the first question and quantify the (topography free) influence of material properties on the probability of finding *J. effusus* we express the CPJ for each material property relative to that for the full study area (Figure 8d-f). This allows us to examine the increase or decrease in probability at a given TWI resulting from that material property. For example, at a TWI of 10, the probability of finding *J. effusus* is reduced by 0.2 on talus and increased by 0.3 on alluvium relative to the full study area (Figure 8e). We can also compare the average difference over the full range of TWIs: -0.08 for talus and +0.24 for alluvium indicating that in general the CPJ of alluvium is 0.32 higher than that for Talus (Table 2).

As we might expect given their lithological similarity, there is still little difference in CPJ between different solid geology types, with maximum differences of <0.25 (Figure 8d) and average differences of <0.08 (Table 2). In particular the two dominant geology types, the Buttermere and Kirk Stile Formations (covering 50 and 41 % of the catchment respectively; Table 2) have CPJs that differ by <0.05 on average. Alluvium, till and alluvial fan deposits remain the surface deposits that are most likely to have *J. effusus*. Alluvium has a high CPJ across almost the full range of TWIs (2-10; Figure 8b). Relative to the full study area it increases the CPJ at a given TWI by 0.24 on average (Table 2) and up to 0.6 in places (Figure 8e). This suggests that independent of topographic location it is very likely to have *J. effusus*. Correcting for topographic location, alluvial fans are still more likely than average to have *J. effusus* (+0.04 in Table 2) but are now less likely to have *J. effusus* than till areas (+0.07). Till and talus, both cover large areas of the catchment (>15 %), but have a very different influence on CPJ. Till has above average CPJs for all TWIs and increases the average CPJ by 0.07 while talus always has below average CPJs and decreases the average CPJ by 0.08 (Table 2). Peat has a low CPJ independent of topography, since *J. effusus* is less able to compete in these nutrient poor environments (Grime *et al.*, 2007). Till, waterlogged loam soils and alluvium have high peak CPJs (0.35, 0.48 and 0.6 respectively in Figure 8a-c) representing a considerable increase relative to the peak CPJ from the topographic index alone (46, 100 and 150 % increases respectively). This suggests that combining information on topography and material properties can considerably improve our ability to predict spatial patterns of *J. effusus* and therefore soil moisture.

To address the second question, assessing the influence of material properties on the relationship between CPJ and topography, we normalise the CPJ for each material property by its maximum for that property. As a result the curves, which look quite different in Figure 8a-c, collapse on top of each other in Figure 8g-i. In particular for solid geology and soil between TWIs of 6 and 10 all curves are very similar. The TWI at which CPJ begins to rise (TWI ~6), the relative rate of that rise, and the TWI at which it reaches its peak (TWI=9-11) are fairly consistent, suggesting that the influence of these material properties on the relationship between topography and CPJ is minimal. The key difference is in the size of the peak at lower TWI values, particularly the large peak for waterlogged loam soils (Figure 8i), which suggests that some cells with high slope or low UCA in these valley bottom soils have *J. effusus* independent of their topographic attributes. This is probably accentuated by the limited sample size (<1 % of the study area) for waterlogged loam soils (Table 2). The drift geology is more complex with noisier curves particularly for alluvium, alluvial fans and blanket peat (Figure 8h); again this is probably partly a result of their limited share of the study area (0.5, 0.7 and 0.8 % respectively). Till and talus have curves similar to that for the full study area, suggesting that they do not disrupt topographic control, while alluvial fans and alluvium weaken or completely disrupt topographic control.

Discussion

In this paper we aimed to test two hypotheses on what drives the spatial pattern of soil moisture regime in a humid temperate upland environment. We did so using *J. effusus* as an indicator enabling us to obtain information on soil moisture patterns over large areas and at a fine resolution. In this section we will: 1) discuss the strengths and limitations to the approach with our recommendations for future application; 2) revisit our hypotheses to establish the extent to which they hold in our study area; and 3) suggest a general conceptual model for soil moisture regimes in our study area.

Our results from a single study site have shown that using vegetation as a surrogate for soil moisture regime identified remotely over large areas represents a potentially powerful tool. Applying this approach more broadly we can begin to quantitatively test the suggestion of Tezlaff *et al.* (2008) that there are landscape scale controls on the relationship between topography and spatial soil moisture. Understanding these controls is essential to inform the application, validation and interpretation of hydrological models. However, the approach should be modified to maximise the available information from vegetation patterns. Whilst we have focussed on a single vegetation community our results show that it is probably necessary to simultaneously map a variety of communities to get a more complete picture of the soil moisture regime in the catchment. Our comparison with observed water table depths confirmed that whilst areas with *J. effusus* will have a 'wet' regime (minimum water table < 0.25 m in 50 % of wells), other areas can have the same regime without *J. effusus.* Our very low CPJ on peat, which we would expect to have a wet regime illustrates that in some areas *J. effusus* becomes an insensitive indicator for soil moisture regime since its presence is being limited by some other aspect of its niche (in this case low pH or nutrient status). Mapping multiple communities should be possible if the communities can be clearly distinguished in the imagery (e.g.

Calluna communities in our study area) but will only be useful if they can both be distinguished and are sensitive to soil moisture rather than other components of their niche.

Our first hypothesis was that the spatial pattern of wet soil moisture regimes is driven by topography. This is based on the assumption that water flowing downslope under gravity, collects in topographic hollows and areas of low slope, resulting in local topographically driven wetness. We have tested three topographic metrics: surface slope, which we assumed defines the hydraulic gradient at a point; UCA, which we assumed defines the volume of water to flow through that point; and the TWI (Kirkby, 1975), which combines these two. Figure 7 shows that topography exerts a strong control on the presence of *J. effusus,* and therefore soil moisture regime in our study area. Figure 7a shows that *J. effusus* patches indicative of a 'wet' regime cluster in a certain part of the slope area space, but doesn't give a clear indication of how this relates to the total population of cells with those topographic attributes. Figure 7b and c show that the distributions of 'wet' cells differ from that for the full study area for slope, UCA and TWI and that the conditional probability that a cell contains *J. effusus* (CPJ) and therefore is wet increases as its slope decreases and as its UCA and TWI increase.

The peak CPJ for slope, UCA and TWI in Figure 7c support the sub-hypothesis that topographic control on soil moisture regime can be best expressed by combining slope and UCA in the TWI in a catchment-scale analysis. The peak probability that a cell contains *J. effusus* conditional on their TWI is significantly higher than that for slope or UCA, reflecting the importance of the two variables in combination, since in isolation their effects may offset each other. Figure 7d shows that once the density of wet (*J. effusus*) cells is displayed as a fraction of the total number of cells with a given slope and UCA we see a different but consistent picture of the zone of maximum *J. effusus* probability. Areas with this combination of slope and UCA are most likely to be *J. effusus* covered and to have the 'wet' soil moisture regime that this indicates. The observations framed in this way (Figure 7d) appear much more consistent with existing theory as characterised by the TWI than those in Figure 7a, although there are still clear differences in the form of the observed relationship compared with that predicted by the TWI. In particular there is a much stronger dependence on slope at high gradients and a much weaker dependence at low slopes than is predicted by the TWI. The CPJ reaches a peak within the slope area domain rather than forming a planar upward trending surface since in areas with high UCA water is flowing over the land surface with sufficient force and frequency to erode the organic soil and vegetation (e.g. rivers or ephemeral gullies).

Our second hypothesis was that the spatial pattern of wet soil moisture regimes is controlled by catchment material properties. Our results suggest that whilst material properties exert an influence on the spatial pattern of soil moisture regimes, which is identifiable through their disruption of the topographic control on soil moisture patterns, it is difficult to relate their influence to mapped patterns of geology and soil type. This probably reflects not only within type variability but also the limitations in detail and resolution in the datasets that we have used to represent these properties.

The bulk material properties of the different rock types within the study area are similar and it is likely to be within type variation in the form of fracture distribution rather than between type variation that drives the soil moisture pattern. This fine scale heterogeneity is visible in Figure 5 where the *J. effusus* indicates both a large but discontinuous wet area in the valley bottom and a series of long thin wet areas on the steep valley sides. Many of the slopes are mantled in a thick layer of glacial till, talus or other surficial deposit (Figure 2); these are likely to lessen any direct solid geological control but do exert some control of spatial soil moisture patterns with the *J. effusus* patterns indicating that wet zones occur predominantly in certain deposits (e.g. till, alluvium and alluvial fan deposits; Table 2). Although these are closely related to their topographic position the same deposits maintain high CPJ even after topographic influences have been accounted for (Figure 8b) suggesting that they have wetter than average soil moisture regimes. The high CPJs attributed to alluvium and alluvial fan deposits indicate wet conditions, which are surprising given that these materials generally have high permeability and storage capacity (Freeze and Cherry, 1979). However, in our study area they are almost exclusively found in the riparian zone (Figure 2) where local topography may be less important than the valley scale topographic setting (discussed further below). The differences between till and talus are perhaps the most striking and useful. Talus makes up 15 % of the catchment but accounts for only 2 % of the *J. effusus* defined wet zones while till makes up 19 % of the catchment and 66 % of the wet zones (Table 2). Both deposits are usually found on the valley sides with talus dominating closer to the ridges (Figure 2), but even after accounting for topographic position CPJs on till are on average 0.15 higher than on talus (Table 2). These results suggest that areas underlain by till are much more likely to be wet than those underlain by talus as we might expect given the higher permeability of talus deposits (Freeze and Cherry, 1979); they suggest that where data on these material properties are available they have the potential to improve prediction of spatial soil moisture patterns. We would also expect that the soil types exert a control on hydrological response; although we know that soil type is spatially variable at a very fine scale and that soil type information available to us is very coarse (Figure 2). In our study area, while soil type does appear to exert an influence on soil moisture regime independent of topography (Figure 8c), it does not correspond well with the material properties recorded for these soils. The low capacity, low permeability peat soils have a slightly lower CPJ than the well-drained loam soils with the greatest storage capacity (Table 2). The seasonally waterlogged loam soils in the valley bottom have very high CPJ, probably as a result of their riparian location (as with alluvium). These results suggest that in this study area soil type data at this scale does not add value to the topographic data in predicting spatial soil moisture patterns. This is more likely to be due to the limitations in the detail and resolution of the data than the influence of soil properties on soil moisture regime.

Figure 6b shows fine scale variability in *J. effusus* pattern, and by extension in soil moisture regime. For example we interpret the *J. effusus* streaks labeled A in Figure 6b as indicative of wet conditions resulting from a series of springs or seepage points at their upslope boundary. Since they often exist in areas where flow convergence is not evident, they represent apparently contingent perturbations to the topographically driven soil moisture pattern. The importance of these perturbations (e.g. springs and seepage points), needs to be reconciled with observed emergent properties at the catchment scale where topography does appear to capture the broad scale soil moisture pattern (e.g. Figure 6a and Figure 7). Our analysis has focussed on slope, UCA and TWI as the topographic predictors of spatial soil moisture pattern. While other topographic information such as elevation and aspect might also be considered, our rationale was in topographic control on the direction and velocity of subsurface flow with its implications for soil moisture. We recognise that wet soil moisture regimes (as indicated by *J. effusus* vegetation) are generated by a range of mechanisms, and in our study area we have identified three main types of wet zone: riparian, topographically-driven and geologically-controlled. Riparian wet zones extend along valley bottoms as a single coherent wet zone beside the river (e.g. B in Figure 6a), they coincide closely with alluvial deposits explaining the very high wetness likelihoods for these deposits. Soil moisture in this zone is driven by groundwater at the valley scale and by hyporheic interactions between the stream and its floodplain. The topographic signal in this area is unlikely to exert a strong influence on soil moisture except at the broadest level; these areas often have low slopes and high UCAs but even areas with higher slopes or lower UCAs are wet. Instead, this zone is likely to be defined by the valley scale topography and by the distance from and elevation above the stream. Topographically-driven wet zones occur towards the base of slopes and in deep hillslope hollows (e.g. C in Figure 6a), they are expected to relate to local slope, UCA and TWI. Alternatively, geologically-controlled wet zones occur downslope from emergent springs (e.g. A in Figure 6a and b) and are therefore not fully described by hillslope topography but probably relate more closely to subsurface structures which due to local geology may or may not be described by elevation, aspect and slope.

Conclusion

Patterns of indicator vegetation species can be readily mapped from the air and can be related to soil wetness and moisture regimes. Here we have demonstrated the potential of this approach using *J. effusus* and although the eco-hydrological niche has not been fully defined, its spatial pattern in our catchment provides a useful proxy for spatial soil moisture patterns and particularly for the location of a wet soil moisture regime.

Topography exerts the dominant control on spatial soil moisture in the study catchment. Combining slope and upslope contributing area in the topographic index improves predictive power increasing the maximum CPJ (the probability of finding *J. effusus* indicative of a wet zone) from <0.2 to 0.25. However, calculating the probability of finding *J. effusus* conditional on both slope and UCA increased the peak CPJ further from 0.25 to 0.34 and identified differences in the form of the observed relationship between CPJ, slope and UCA relative to that predicted by the topographic index. This provokes us to re-examine the way that slope and UCA combine to drive spatial soil moisture patterns but we need to explore this relationship further in other settings before we can formulate it with confidence. Soil material properties co-vary strongly with topography across catchments making their influence on spatial soil moisture more difficult to untangle. However, they exert a significant influence that can be assessed after controlling for topography; and in combination with topography they improve predictive power, increasing the peak probability of finding *J. effusus* to up to 0.6 in our study area.

Further work is required to define the eco-hydrological niche of this and other vegetation species in order to fully capitalise on this relationship but this pilot study has shown its potential to provide high resolution information on wetness patterns at the catchment scale. Furthermore we have shown the potential that this approach has in reconciling the complexity of detailed hillslope studies with the emergent properties visible at the larger catchment scale.

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Figures

Figure 1: A mosaic of the orthorectified aerial photographs for the Newlands valley study area (outlined in red). The black box labelled A shows the extent of the study hillslope.

Figure 2: The spatial pattern of *J. effusus* (black) projected onto maps of the study area showing: a) solid geology including the Robinson Member (RNM) and Buttermere (BUF), Kirk Stile (KST) and Loweswater (LWF) Formations; b) surficial geology, c) shaded relief and d) soil type. Maps a and b include British Geological Survey (BGS) data compiled from Geology Digimap – Geological Map Data © Natural Environment Research Council, 2011; Map d includes soils data from the National Soils Research Institute.

Figure 3: Box plots showing water table information from maximum stage recorders deployed in 95 wells in a Lake District hillslope (labelled A on Figure 1) over two measurement periods (11/06-02/07 and 02/07-05/07). They are grouped by overlying vegetation type and show a) maximum depth to the water table and b) depth to the water table as a percentage of the depth to bedrock at each well.

Figure 4: Exceedance probability for water table depth for *J. effusus* and the full study area (a) and the mean (solid line) +/- 1 sigma (dotted line) probability of finding *J. effusus* at a well in the study site given its water table depth (b). The dashed grey line shows the site average probability of finding *J. effusus* (0.10).

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Figure 7: (a) upslope contributing area against local slope for all the cells in the study area (light green) and wet cells only (dark blue), dashed black lines are topographic index contours; (b) probability distributions of topographic index, slope and upslope contributing area for all cells in the study area (dashed green) and wet cells only (solid blue); (c) the mean (solid red line) +/- 1 sigma (dotted red line) conditional probability of finding *J. effusus* (CPJ) for the same topographic variables as b, the black dashed line indicates the catchment average probability of finding *J. effusus* (0.04); (d) contour plot (red) showing the CPJ surface in slope area space with dashed black topographic index contours.

Figure 8: (a-c) the conditional probability of finding *J. effusus* (CPJ) given topographic index for the study area classed according to its material properties: Solid Geology, Drift Geology and Soil Type; (d-f) the difference between the CPJ for each material property and that of the full study area; (g-i) the CPJs normalised as a fraction of the maximum CPJ for that material property (CPJ*). The dark red curve in a-c and g-I shows the CPJ for the full study area.

Tables

Table 1: Natural limits and tolerances of dominant species within the study area using data from the Ecological Flora Database (Fitter and Peat, 1994).

Species	Max Altitude	pH range	Soil Moisture (Ellenberg F)
J. effusus	[1] 853 m	[2] 3.9 – 6.6	[3] 7
C. vulgaris	[4] 1095 m	[5] 3.05 - 6.5	[3] 6
P. aquilinum	[6] 600 m	[7] 2.8 – 8.6	[3] 5

[1] Wilson (1949); [2] Richards and Clapham (1941); [3] Hill *et al.* (1999); [4] Gimingham (1960); [5] Gimingham (1972); [6] Clapham *et al.* (1962); [7] Marrs and Watt (2006).

Table 2: Relationships between *J. effusus* and solid geology, surficial geology and soil expressed as: the percentage of the full study area with that property; the percentage of the *J. effusus* covered zones with that property (by area); the conditional probability that a cell contains *J. effusus* given that property (CPJ); and the average difference in CPJ for that property relative to the full study area (i.e. the area under the curve in Figure 7d-f). Note that *J. effusus* covers 4 % of the full study area.

	Full Study Area (%)	*J. effusus* Zones (%)	Conditional Probability of *J. effusus* (CPJ)	Average Difference in CPJ
Solid Geology				
Buttermere Formation	49.7	56.5	0.05	+0.03
Kirk Stile Formation	41.1	39.9	0.04	-0.02
Loweswater Formation	4.4	0.4	0.00	-0.07
Robinson Member	3.9	3.0	0.03	+0.05
Other	0.8	0.2	0.01	
Surficial Geology				
Alluvial Fan	0.5	2.2	0.17	+0.04
Alluvium	0.7	7.5	0.45	+0.24
Blanket Peat	0.8	0.8	0.04	-0.06
Talus	15.4	1.8	0.01	+0.08
Till	18.9	66.3	0.14	0.07
None	63.7	21.3	0.01	
Soil				
Peat	36.9	20.2	0.02	-0.03
Well-drained loam	61.8	74.4	0.05	+0.01
Waterlogged loam	0.9	5.3	0.25	+0.11
Other	0.5	0.1	0.01	

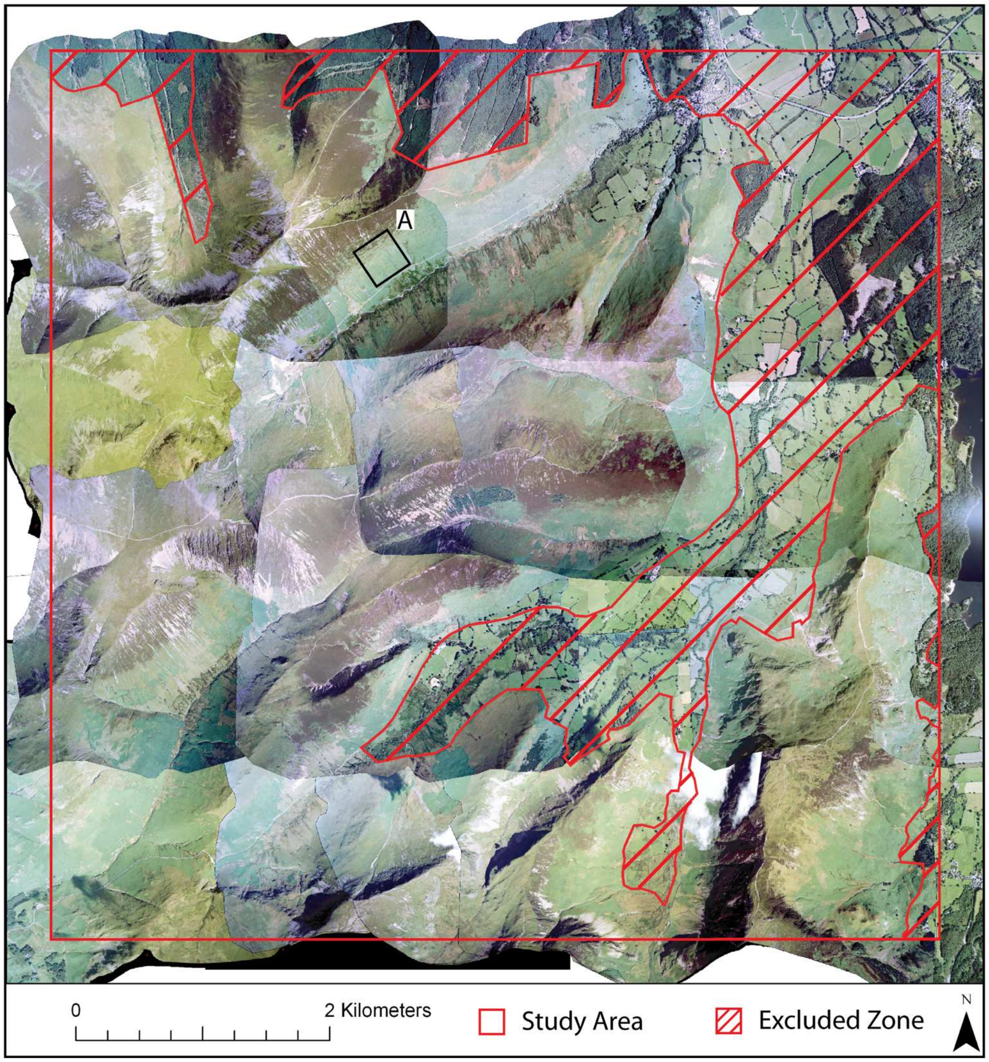

Figure 1: A mosaic of the orthorectified aerial photographs for the Newlands valley study area (outlined in red). The black box labelled A shows the extent of the study hillslope.
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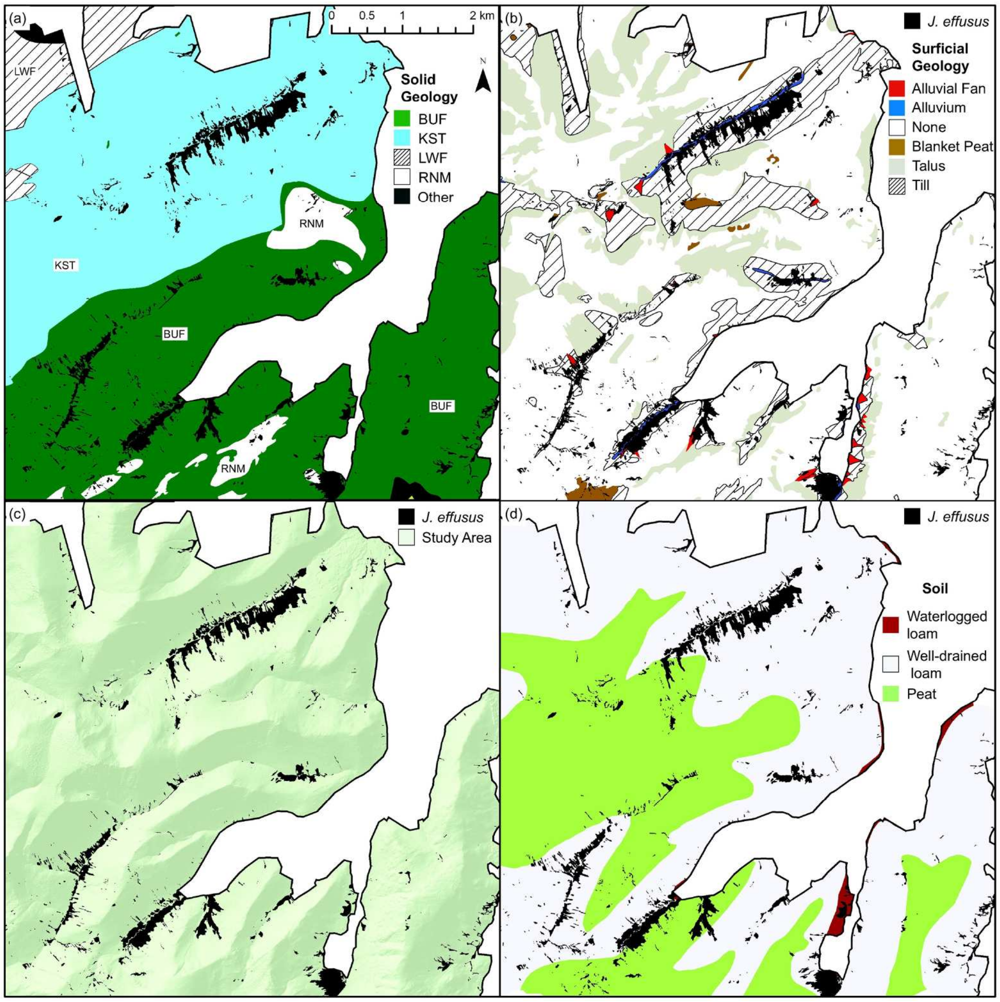

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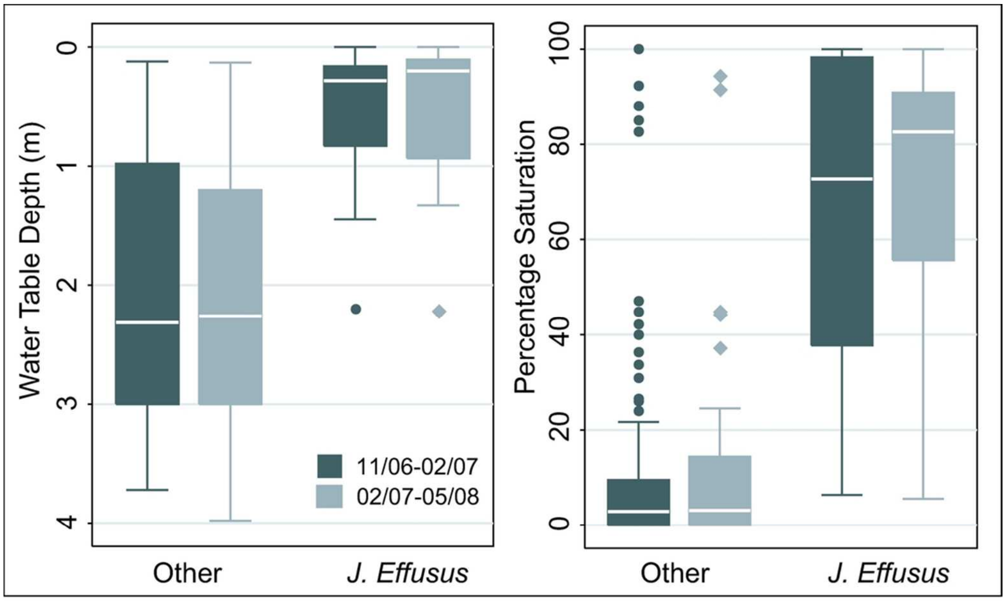
196x196mm (300 x 300 DPI)



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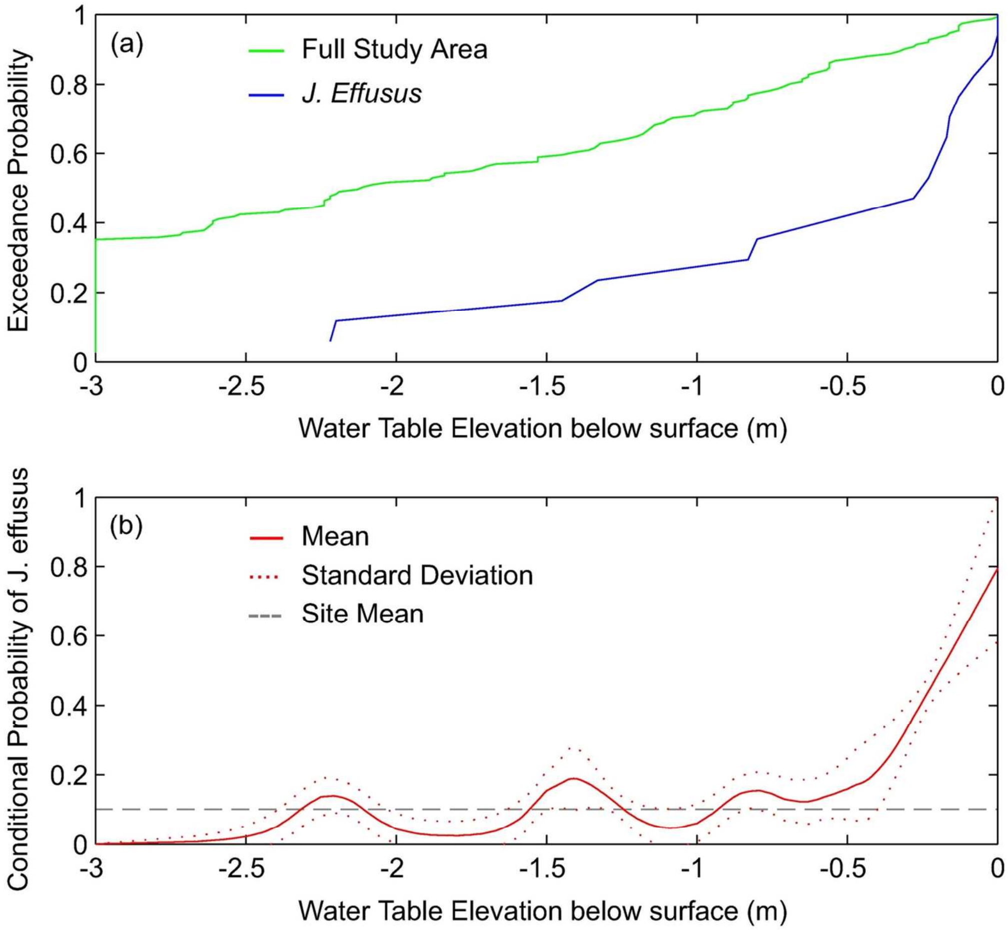

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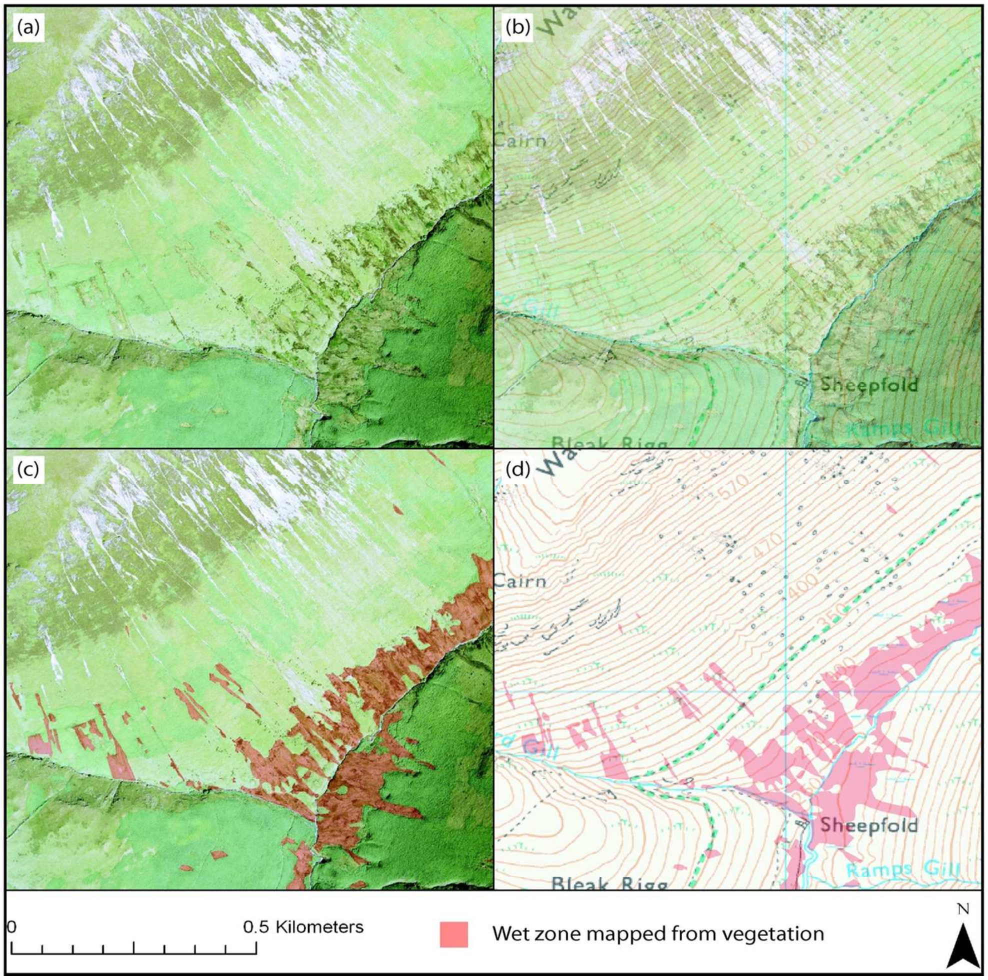
120x111mm (300 x 300 DPI)



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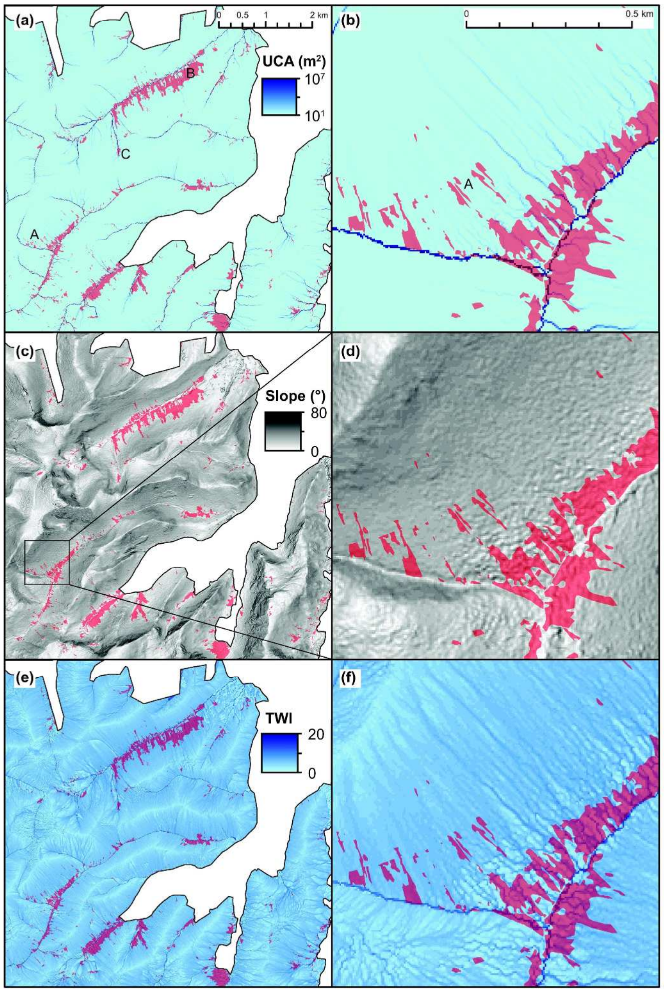

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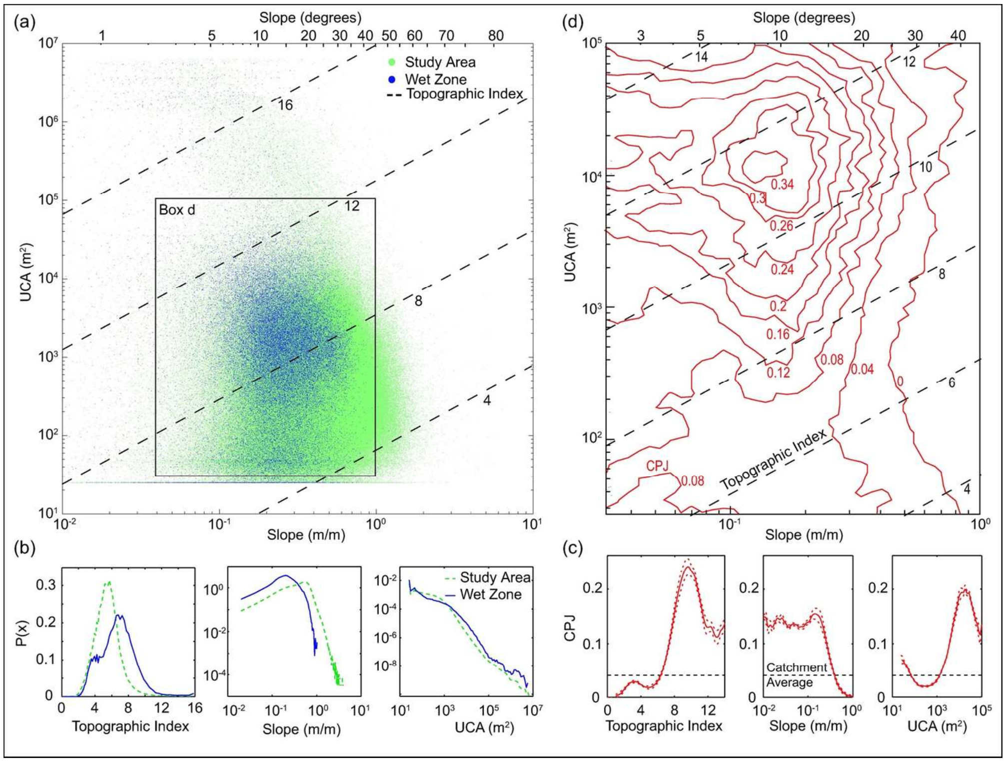
279x361mm (300 x 300 DPI)



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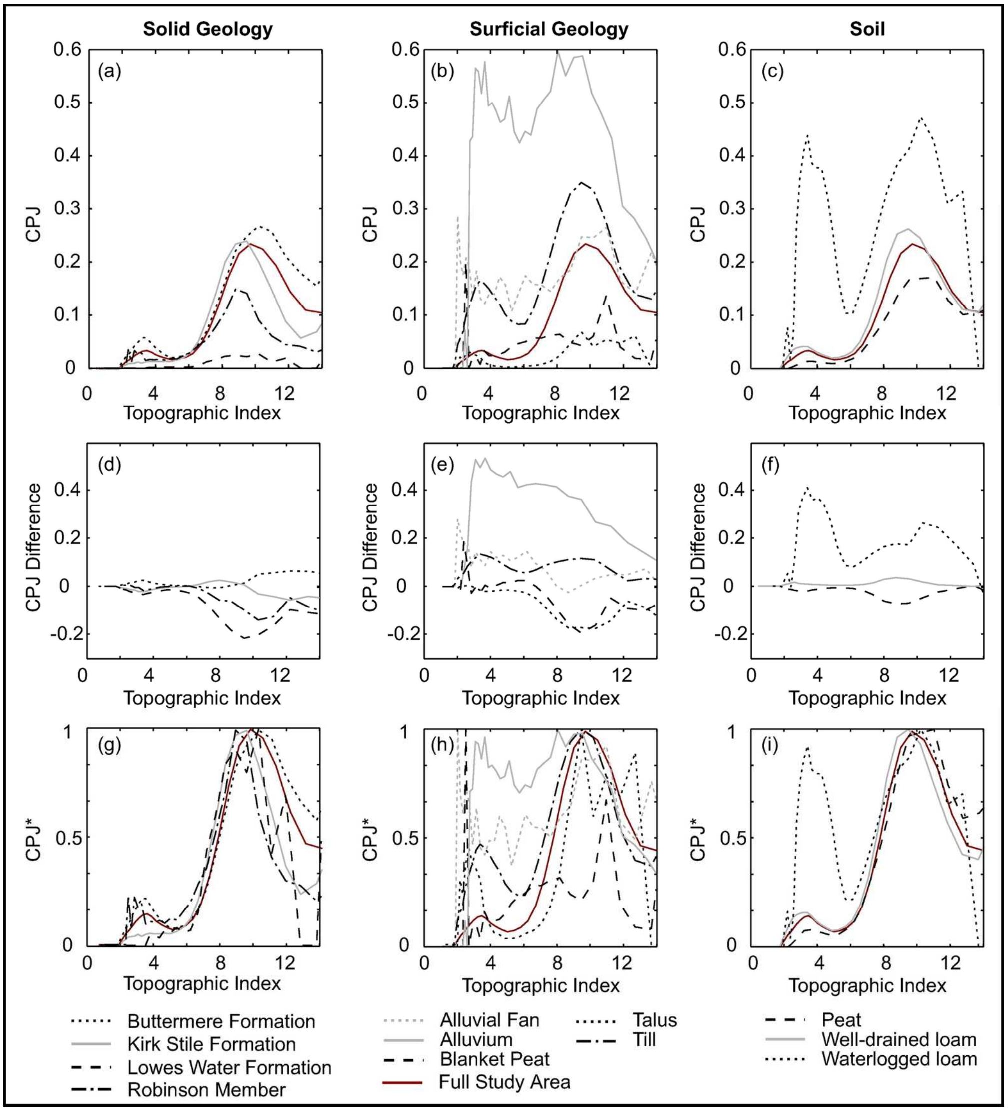
148x111mm (300 x 300 DPI)



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160x177mm (300 x 300 DPI)