09 - EVALUATING THE EFFECTIVENESS OF THE NITRATES DIRECTIVE IN IRELAND FOR NUTRIENT LOSS – THE AGRICULTURAL CATCHMENTS PROGRAMME

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Abstract
The Agricultural Catchments Programme is evaluating the biophysical and socio-economic impacts of the Nitrates Directive National Action Programme through high resolution spatio-temporal monitoring in six agricultural catchments across Ireland. A source to impact conceptual model provides the basis for the biophysical research programme. Phosphorus and sediment dynamics in the five stream catchments are the focus of this paper. Phosphorus concentrations in rivers provide a chemical indicator of water quality status linked to ecologically based Q values (macro-invertebrates and diatoms). Three catchments were deemed high risk of phosphorus (P) loss due to their moderate to poorly drained soils and high potential for overland flow. Two catchments, with predominantly well drained soil and permeable geology were deemed low risk of overland flow and hence P transfer.

Phosphorus concentrations were measured in-situ on a sub-hourly basis using bankside analysers and discharge was monitored at rated non-standard flat-v weirs. Phosphorus loads were calculated as the product of concentration and discharge. Suspended sediment (SS) concentration and load was derived from turbidity – SS relationships where turbidity was also measured in-situ on a sub-hourly basis. Factors influencing P loads and concentrations were explored in GIS using a surface hydrological connectivity model derived from a 5m Digital Elevation Model (DEM) and field and farm information on nutrient sources. In two focus sub-catchments, the base DEM was modified to include ditches networks to better define surface flow path connectivity.

Annual P loads (<1 kg ha^{-1}) were similar to or lower than observations from intensive rural catchments in Northern Ireland and Europe, however, annual mean P concentrations were often above the Irish surface water regulation of 0.035 mg L^{-1} reactive P. Suspended sediment loads were lower than general estimates of soil formation rates (up to 1 t ha^{-1} yr^{-1}). Flow hydrographs revealed that flashy storm discharge and low baseflow contributions were associated with higher P and SS loss as anticipated for two of the poor to moderately drained catchments, particularly during the autumn and winter. Higher P losses than expected from the well-drained dairy grassland catchment highlighted the potential for subsurface P movement in this landscape.

The susceptibility of catchments to overland flow and P and SS transfer will be discussed along with the types of data and geostatistical tools (e.g. ground-truthed soil maps, surface connectivity maps, drainage features, land use, groundcover and nutrient source patterns) that can be used to better represent nutrient transfer processes at the catchment scale. Implications of the observed exported loads and in-stream nutrient concentrations in agricultural catchments is also discussed in terms of policy expectations for meeting Water Framework Directive objectives.

1. Introduction

The Agricultural Catchments Programme (ACP) is operated by Teagasc and funded by the Department of Agriculture, Food and the Marine. The objectives are to provide a catchment scale evaluation of the package of measures in the Nitrates Directive National Action Programme (NAP) and associated Good Agricultural Practise regulations. This policy also provides the Programme of Measures as required under a suite of river basin scale water resource mitigation and protection measures under the Water Framework Directive (WFD). As Ireland's NAP is based on a 'whole-territory' approach, all agricultural landuse is subject to regulation that constrains the magnitude and timing of nutrient management or the processes that influence mobilisation. This means limits on livestock intensity and nutrient applications, closed periods for slurry, chemical and farmyard manure fertilisers and limits on when bare soil, for example from ploughing, can be left exposed to rainfall. Phase 1 of the ACP was from 2008 to 2011 and Phase 2 will run from 2012 to 2015.

Five agricultural stream catchments and one emergent spring from a karst limestone zone of contribution (Fig.1) were chosen using national spatial datasets where the soil type and geology, and the level of agricultural intensity were prime factors (Fealy *et al.* 2010). The five stream catchments range from 4 to 12 km^2 in size, a scale that is manageable in terms of giving a community ownership in the project through Teagasc advice networks and meaningful in terms of being able to isolate the major agricultural landuses from municipal, industrial or other sources of nutrients.

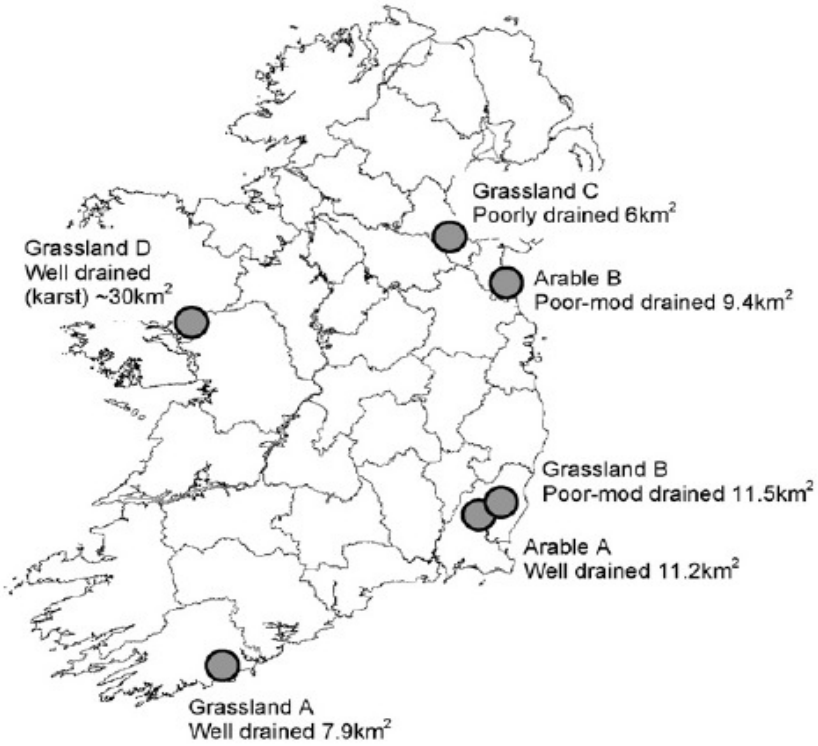


Figure 1. Location of six study catchments in the Agricultural Catchments Progamme (from Jordan et al. – in review)

The main soil types, bedrock geology and topography of the five stream catchments (Grassland A, B and C and Arable A and B) are summarised in Table 1. Based on the previously mapped proportion of poorly drained soils and impermeable bedrock, the percentage area at extreme of P loss in overland flow was estimated using the method of Fealy *et al.* (2010) and ranged from a 2% potential in Grassland A to an 87% potential of the catchment in Grassland C.

Table 1. Dominant soil, geology, landuse and predicted percentage area of extreme P transfer risk via overland flow for five agricultural catchments

Catchment	Dominant farm systems	Arable land use, %	Soil Type	Bedrock	Area of extreme P transfer risk, %
Grassland A	Dairy: grassland Dairy: grass & maize	4	Brown Podzolic	Red Sandstone, mudstone	2
Grassland B	Dairy: grassland Beef:grassland	19	Gley	Rhyolitic volcanics, slates	80
Grassland C	Beef:grassland Sheep:grassland	0	Acid Brown Earth	Fine to Coarse Turbidites	87
Arable A	Spring barley Oil seed rape/ winter wheat	54	Acid Brown Earth	Slate, Siltstone	11
Arable B	Winter wheat Beef: grassland	32	Grey Brown Podzolic	Calcareous greywacke, mudstone	73

Catchment water quality responses to the current NAP measures, and to past management are monitored through an intensive study of the nutrient transfer continuum (Haygarth 2005) from source to impact (Wall *et al.* 2011). In this paper we describe the susceptibility of the five stream catchments to phosphorus (P) and suspended sediment (SS) transfers and discuss the implications of the observed exported loads and in-stream concentrations in terms of policy expectations for meeting Water Framework Directive objectives. We also discuss the potential for a topographically derived surface hydrological connectivity index and observed catchment data to improve spatial representation of nutrient transfer risk at the catchment scale.

2. Methods

Stream phosphorus and suspended sediment

Each of the catchments has a similar monitoring routine and infrastructure for discharge, P and SS measurement. Catchment outlet infrastructure consists of Corbett flat-v non-standard weirs with water level recorders rated for discharge using acoustic Doppler flowmeters (Plate 1), and automated bankside instrumentation programmed to collect and analyse water chemistry (total P (TP), total reactive P (TRP) and turbidity) on a sub-

hourly basis (Plate 2). Water quality measurements are taken in an enclosed header tank on a pump-loop system.

Stream P concentration is monitored using a Dr Lange Phosphax-Sigmatax suite of instruments that use a fully automated colorimetric analysis. The equipment analyses unfiltered river water samples for total digested P (TP) and total molybdate-reactive P (TRP) concentrations from 0.01 mg L^{-1} to 5.00 mg L^{-1}. The TRP fraction is operationally defined as MRP in Irish monitoring terminology. The method alternates the digestion step to give up to 3 TP and up to 3 TRP data-points in each hour. Turbidity is measured every 10 min using self cleaning turbidity probes (Hach-Lange Solitax 0-1,000 NTU). Turbidity data are routinely compared with datasets of suspended sediment concentrations of samples taken periodically directly from the stream outlet and calculated as the dried residue on 1.2µm glass fibre filter-papers. Preliminary turbidity-suspended sediment concentration relationships have been derived and applied to the sub-hourly turbidity datasets. Data are held in an internal logger and also transferred to a Netrix GPRS data-push system to hold on a web-enabled SQL server (Dexdyne Ltd.) for real-time and historic data visualisation. Hourly P and SS loads in streamflow are calculated as the product of the mean hourly concentration of total P and SS respectively, and hourly discharge in a final quality control and archive database (WISKI 7).

Plate 1. Typical hydrometric station set-up on ACP stream catchment outlets. A low-profile non-standard Corbett flat-v weir acts as a control for two water level measurements that are rated to discharge with OTT acoustic Doppler flowmeters using the mean-panel method (20cm panels).

Plate 2. Bankside water quality equipment used in the ACP. The central unit is an automated P analyser sampling water on a sub-hourly basis from the black header tank (left) where turbidity (and nitrate, conductivity and temperature) are also measured.

Surface hydrological connectivity

Relative connectivity of surface flow pathways was calculated using a Network Index (NI) of Lane *et al.* (2009) in each catchment using a 5 m resolution DEM (INTERMAP). The NI uses the DEM to calculate an index of topographically driven surface flow for each pixel and then assigns relative connectivity based on the lowest NI connectivity score along a flowpath to the nearest downstream channel or reservoir. Mean channel dimensions of all ditch reaches (where a reach is the length of a field) in the Arable A and Grassland B catchments were also surveyed and captured as attributes in a geodatabase of field and field boundary polygons. A rastor layer of ditch depths was created and were subtracted from the catchment DEM. The observed ditches ranged from 0.5 to 2 m deep and 0.5 to 4 m wide. Slopes at the ditch edges were likely to be exaggerated due to the finer spatial resolution of ditch dimension observations compared with the coarser DEM resolution. The NI was re-calculated for these two catchments after the DEM was modified with observed ditches and NI outcomes were compared with the original DEMs (i.e. without ditches burnt in).

3. Results and discussion

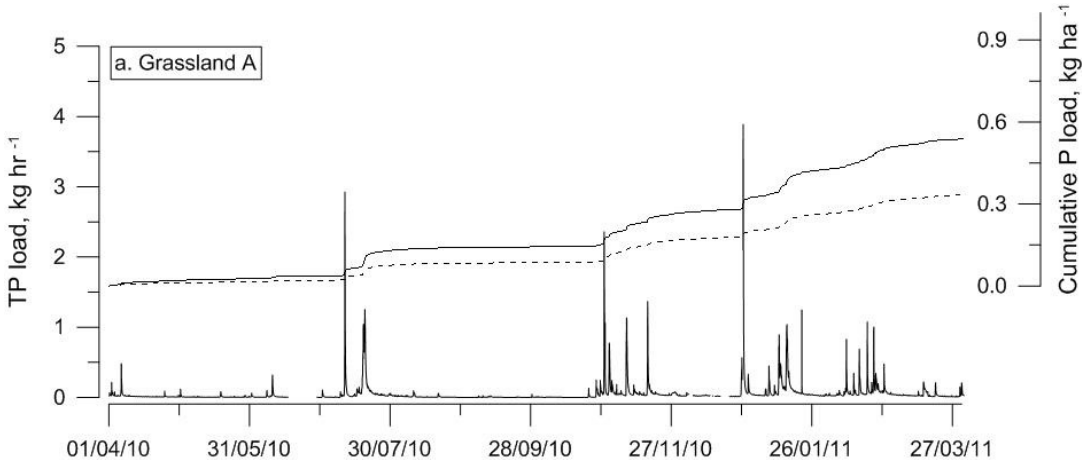
Annual P loads for the period 1st April 2010 to 31st March 2011 (Table 2) were less than <1 kg ha^{-1} from all catchments. For comparison, a similar range of average annual total P loads (0.1 – 0.9 kg P ha^{-1}) was measured from larger mainly arable agricultural catchments (175 – 5,373 ha) in Sweden, where the higher loads were related to heavier soil types, higher rainfall and a larger proportion of annual crops (Kyllmar *et al.* 2006). Given the high annual rainfall (Table 2) these loads were not high relative to those measured from intensive agricultural catchments/systems dominated by either cropping (0.5-2.4 kg ha^{-1}, (Kronvang *et al.* 2005) or grassland (0.1 – 1.6 kg P ha^{-1}, (Jordan *et al.* 2005) elsewhere in Ireland and Europe. However, annual mean P concentrations were often above the Irish surface water regulation of 0.035 mg L^{-1} total unfiltered reactive P (but comparing over 8,000 datapoints in a year with the (up to) 12 generally used as a mean in the regulations). The annual loads of SS delivered to catchment outlets (37 – 155 kg ha^{-1}) were lower than the 540-1,210 kg ha^{-1} observed from a 46 ha grassland headwater stream (Bilotta et al 2010) and were below rates of soil loss considered 'tolerable' in relation to approximated rates of soil formation of about 1,000 kg ha^{-1} in Europe (Verheijen *et al.* 2009). To evaluate the environmental significance of the SS transfers in streamflow, however, the off-site impacts also need to be considered; i.e. impacts on in-stream aquatic ecology, and this is under investigation by the ACP (Melland *et al.* 2010).

Figure 2 shows a higher rate of P loss due to storm activity in autumn than the spring and summer across the four stream catchments with complete hydrological year data available (or two water half years in this example). The rate of increase and individual storm load peaks were greater for the less well-drained catchments (Grassland B and Arable B) than the better drained catchments (Grassland A and Arable A). However, P loads were higher than anticipated in Grassland A: P transfers in subsurface pathways are being investigated in this catchment.

Table 2. Rainfall, discharge, total P load, total reactive P mean concentration and suspended sediment (SS) load observed during the hydrological year April 1st 2010 to March 31st 2011.

	Grassland A	Grassland B	Grassland C	Arable A	Arable B
Rainfall, mm	1019	939	427*	857	791
Discharge, mm	503	413	366*	491	393
Q5:Q95	32.5	65.9	na	10.7	83.0
TP, kg ha^{-1}	0.541	0.701	0.171*	0.175	0.785
TRP, mg L^{-1}	0.049	0.061	0.023*	0.026	0.109
SS, kg ha^{-1} (approx)**	37	130	50*	49	155

* Data only available from November 1st 2010 – March 31st 2011; na – not available.
** Rating curves still under development.



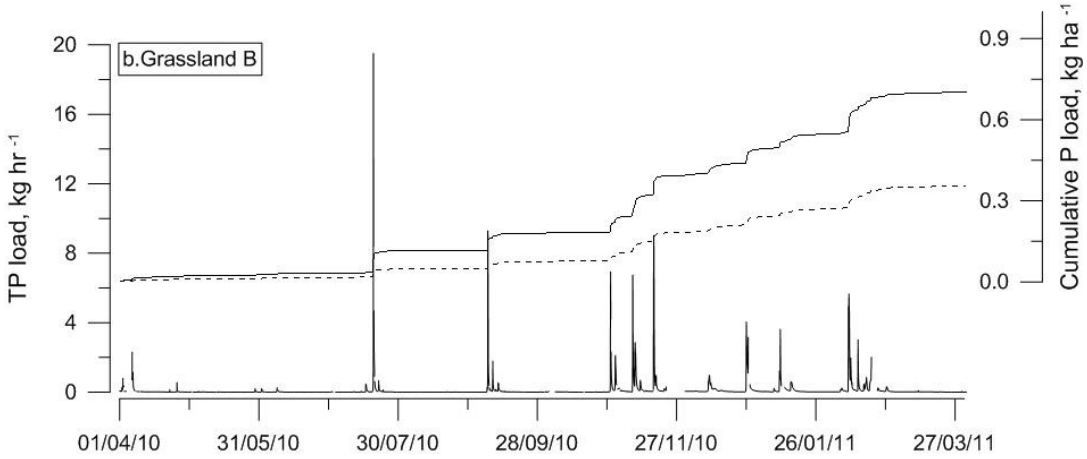


Figure 2. Continued over.

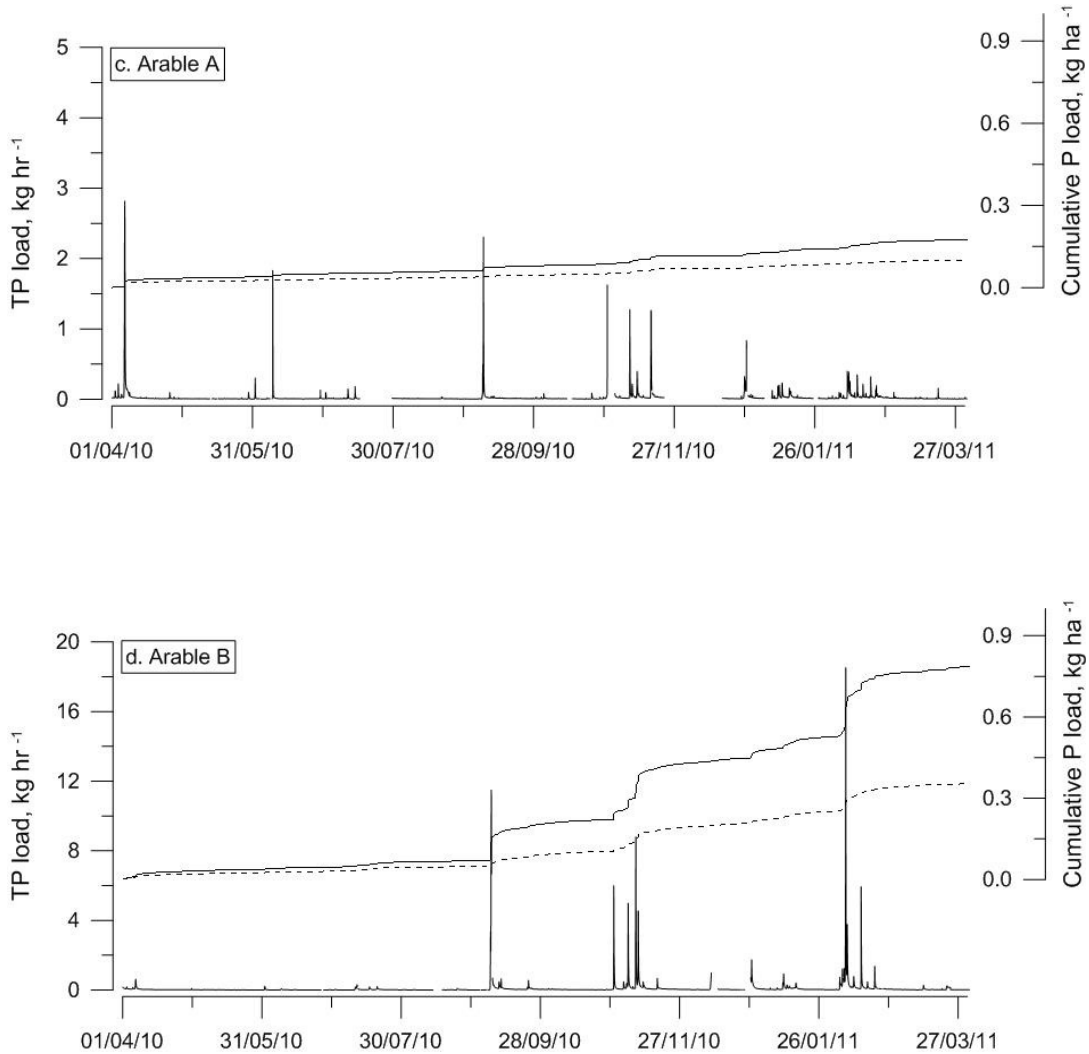


Figure 2. Time series charts showing hourly TP load (as chemographs) and the evolution of both TP (solid line) and TRP (dashed line) cumulative loads over a one year cycle in well drained (a, c) and poorly drained (b, d) grassland and arable catchments. Note different scales of first y-axes. From Jordan et al. in review.

Overland flow risk comparisons between catchments: flow metrics

The dominant influence of flow regime on P exports is further exemplified for these four catchments by a positive linear relationship between the percentage of P transferred in streamflow during the period closed for spreading of fertiliser, slurry and farm yard manure and the Q5:Q95 for the same period (Figure 3, Jordan *et al.*, in review). The Q5:Q95 metric is an approximate reflection of the flashiness of stream flow where the higher the ratio, the lower the baseflow contribution to total flow. The relationship occurred despite lower diffuse surface P sources in Grassland B, which exported the highest proportion of total P load during the closed period. The relationship suggests that the annual and closed period Q5:Q95 are useful indicators of relative differences in flow regime and closed period P transport risks, respectively, between catchments. The

indicator integrates the impacts of within catchment variance in soil type and topography on stream flow.

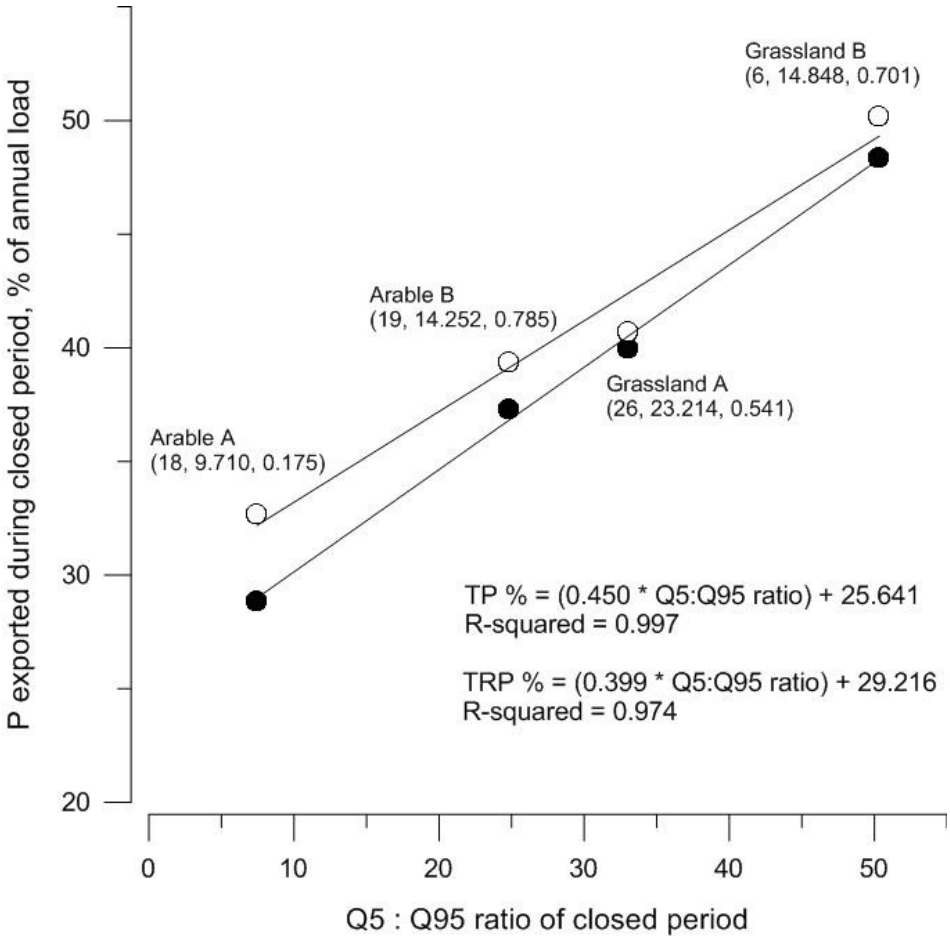


Figure 3. A metric of runoff flashiness (Q5:Q95 ratio) as a controlling factor for the proportion of P exported during the closed slurry spreading period (15th 21 October to 15th 22 January). Data in brackets indicate the area-weighted percentage soil P index 4 in each catchment, the annual organic P loading (kg ha-1 yr-1 and total TP load, respectively. From Jordan et al. – in review.

Stream P loads are important determinants of the trophic status of standing and transitional waterbodies and will have a variable influence on ambient concentrations in rivers, that depend on the attenuation and subsequent in-stream mobilisation potential of the lotic environment. Figure 2 shows that annual stream loads of P are dominated by storms. Because of increased nutrient loads during storms, when surface runoff pathways are active, the relative potential for surface runoff compared with subsurface contributions to streamflow may be a crucial factor influencing the effectiveness of the environmental measures such as the NAP regulations (Appels *et al.* 2010). The Q5:Q95 ratio may provide a reliable and pragmatic indicator of surface runoff potential. Theoretically, catchments with the greatest surface connectivity should have the greatest opportunity for land surface changes implemented through the NAP to have an impact.

In terms of the temporal effectiveness of the NAP for P loss, Figure 2 shows that in all four catchments, more than 25% of the total annual P load was exported during the closed period, which represents 25% of the time. These disproportionately high loads support the logic of restricting nutrient mobilising activities during this period. However, the remainder of the year can still present high nutrient pressure in the form of concentrations for lotic ecology during the summer months. Importantly, connectivity of land P sources is diminished during low flows in summer so the potential for NAP measures to mitigate eutrophic impacts may also be dimished outside the closed period.

Topographic & landscape feature metrics: Hydrological connectivity

Whilst inter-catchment P and SS transfer risk may be broadly defined by soil type, geology and flow regime, within catchment risks are likely to be further influenced by topography. A second tool for catchment P and suspended sediment transfer risk assessment that is being explored is the use of DEM data, which is a more readily available than flow data. Ditch density (excluding streams) was much higher in catchment B (5,865m km^{-2}) than catchment A (1,271m km^{-2}) reflecting the poorly drained soils in the lowlands of Grassland B. The ability of the original surface hydrological connectivity NI model to predict location and direction of flow (represented by the surveyed ditch network) improved as the scale increased; however, inaccurate prediction of observed surface flow direction at the field scale was substantial (Figure 4a). The modified NI model provided a more accurate representation of observed flow direction at all scales largely because alignment with the ditch network was substantially improved at the field scale (Figure 4b). Comparison of mean connectivity scores between the original and modified NI for Arable A, illustrated that including ditches into the 5 m DEM reduced the connectivity within fields, ditch networks watersheds and subcatchments, while increasing the connectivity within the ditch and stream channels (Figure 4c).

The modeled and observed potential for ditches to reduce in-field surface connectivity and increase connectivity within the drainage channels has important implications for accurately identifying critical sources areas (CSAs) for nutrient loss in the landscape. For example, application of the original NI model may over-estimate the presence of CSAs in ditch-rich landscapes, and underestimate the role of within-channel connectivity. Higher connectivity within channels may reflect greater connection of other parts of the landscape such as direct connection with uphill fields and channels, and contributions from subsurface pathways.

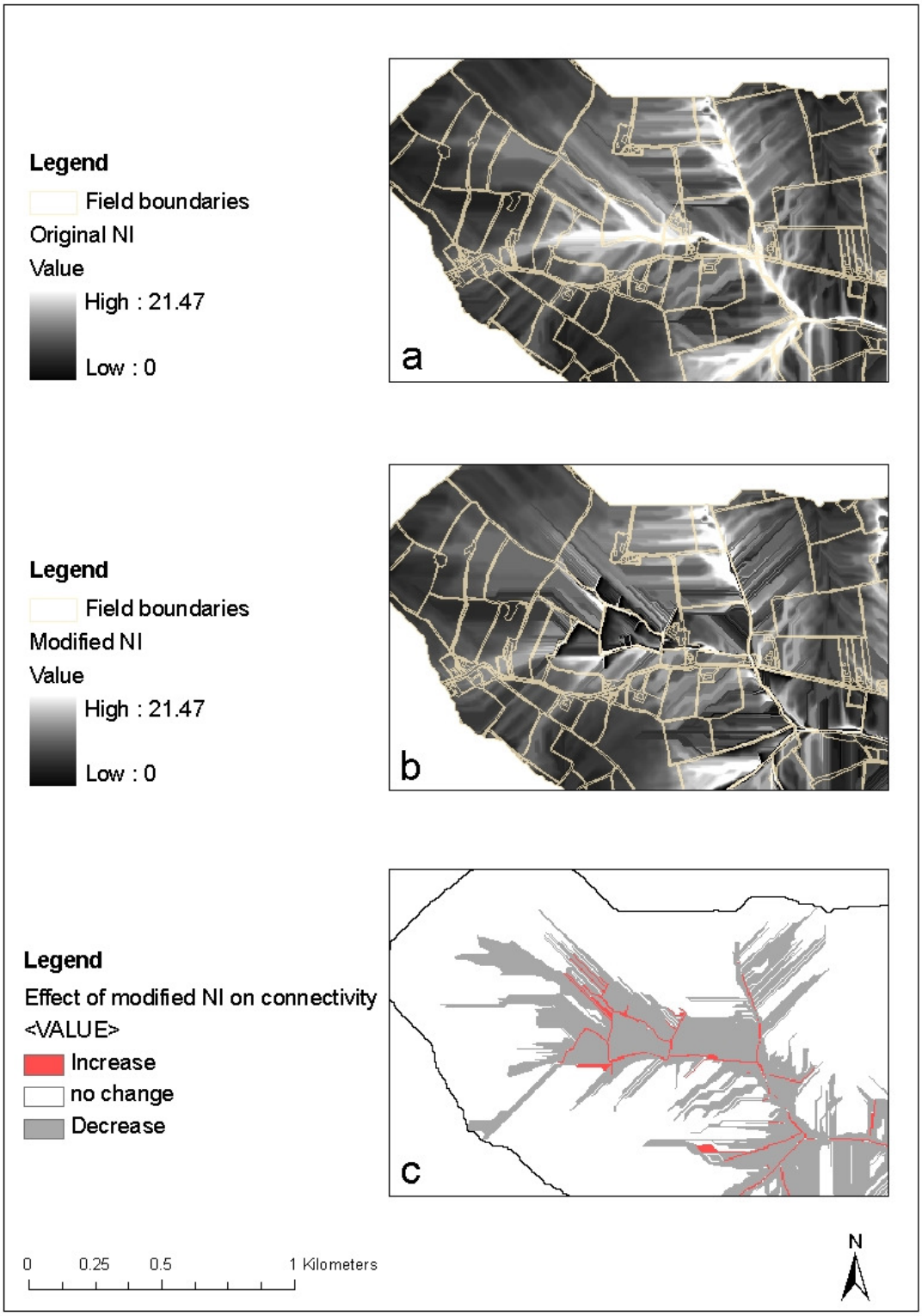


Figure 4. A representation of the NI connectivity scores for a headwater of the Arable A catchment a) without ditches and b) with ditches 'burned' into the base DEM. Field boundaries also shown. Change in NI connectivity score c) in a headwater of the Arable A catchment as a result of 'burning' ditches.

4. Conclusions

Annual P and SS loads from the five stream catchments were relatively low in the hydrological year April 1st 2010 – March 31st 2011. However, annual mean P concentrations were often above the Irish surface water regulation. Flow hydrographs revealed that flashy storm discharge and low baseflow was associated with higher P and SS loss as anticipated for two of the poor to moderately drained catchments, particularly during the autumn and winter.

Analytical tools that have proven useful for characterisation of the susceptibility of catchments to overland flow, P and suspended sediment transfer include broad soil type and geological assessments and the Q5:Q95 ratio for gauged catchments. A topographically driven indicator of surface hydrologiocal connectivity, the Network Index, modified by inclusion of ditches in the derivative 5m DEM was useful for identifying the likely location of surface flow paths. These tools may help define where overland flow, P and SS transfers are most likely and therefore where measures to minimise these losses may be most effective.

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