The short-term effects of management changes on watertable position and nutrients in shallow groundwater in a harvested peatland forest

J. Finnegan[a], J.T. Regan[a], O. Fenton[b], G.J. Lanigan[b], R.B. Brennan[a], and M.G. Healy*[a]

[a]Civil Engineering, National University of Ireland, Galway, Ireland
[b]Teagasc, Environmental Research Centre, Johnstown Castle, Wexford, Ireland

* Tel +353 91 495364 fax +353 91 494507, email: mark.healy@nuigalway.ie

ABSTRACT

Management changes such as drainage, fertilisation, afforestation and harvesting (clearfelling) of forested peatlands influence watertable (WT) position and groundwater concentrations of nutrients. This study investigated the impact of clearfelling of a peatland forest on WT and nutrient concentrations. Three areas were examined: (1) a regenerated riparian peatland buffer (RB) clearfelled four years prior to the present study (2) a recently clearfelled coniferous forest (CF) and (3) a standing, mature coniferous forest (SF), on which no harvesting took place. The WT remained consistently below 0.3 m during the pre-clearfelling period. Results showed there was an almost immediate rise in the WT after clearfelling and a rise to 0.15 m below ground level (bgl) within 10 months of clearfelling. Clearfelling of the forest increased dissolved reactive phosphorus concentrations (from an average of 28 to 230 µg L^{-1}) in the shallow groundwater, likely caused by leaching from degrading brash mats.

Keywords: forestry, peat, clearfelling, watertable, groundwater, nutrients

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1.   Introduction

Ireland's forest cover stands at 10% (698,000 ha) of the total surface area of the island, and 59.6% of total forest estate is on peat (Forest Service, 2007). The current trend is for afforestation to take place on more suitable soil types, leading to increased productivity and enhanced environmental quality (EPA, 2012). However, the legacy of blanket peatland forestry, planted in the 1950s, must be dealt with, as most of this forestry is now at harvestable age and the decision to either reforest or restore these sites needs to be made (Renou-Wilson et al., 2011). The economic viability of such plantations on upland peat is limited (Renou and Farrell, 2005), with over 40% of the forestry having poor production potential (Tierney, 2007). As the depth to the watertable (WT) affects nutrient dynamics, any potential impact of forestry activities, such as harvesting, reforestation or restoration, on blanket peat soils needs to be quantified.

Drainage of peatlands for agriculture or forestry purposes lowers the WT and can impact on greenhouse gas emissions (Erwin, 2009; Wichtmann and Wichmann, 2011) and water chemistry (Blodau, 2002). A lowered WT increases aeration, which results in enhanced nitrate (NO_3^-) concentrations in the pore water. In addition, phosphorus (P) is sorbed to iron (Fe) or aluminium (Al) hydroxides and becomes immobilised (Zak et al., 2004). Rewetting of peatlands aims to return the WT back to its original position through management changes. Re-wetting decreases nitrogen (N) mineralisation (Urbanová et al., 2011), but may lead to the enhancement of P mobilisation (Tiemeyer et al., 2007).

The 'European Parliament Resolution on Wilderness in Europe' (EU, 2009) aims to create amenity areas and enhance biodiversity by (amongst other measures) restoring

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unproductive blanket peat to native wilderness. Coillte, the Irish State's current forest management company, carried out a number of restoration projects on various types of peatlands (raised bogs (Coillte, 2008a), blanket bogs (Coillte, 2008b) and priority woodlands (Coillte, 2010)) between 2004 and 2009, and over the next 15 years, Coillte proposes to take 4,400 hectares out of commercial forestry and create wilderness from it (Coillte, 2013). This harvesting of forests may have an impact on WT and shallow groundwater chemistry. As there is sometimes conflicting information in the literature regarding the impact of WT change on nutrient mobilisation (Tiemeyer et al., 2007; Urbanova et al., 2011; Macrae et al., 2013), it is necessary to examine the impacts of WT changes on nutrient release. Therefore, the aim of this study was to investigate, over two years including pre- and post-clearfelling periods, how clearfelling of a forest on a blanket peat soil affects (1) WT fluctuations and (2) P and N concentrations in shallow groundwater.

2.   Materials and Methods

2.1.   Study Site Description and Management

The study site was located in the Altaconey (also known as the Altahoney) forest in the Burrishoole catchment in Co. Mayo, Ireland (ITM reference 495380, 809170) (Figure 1). The catchment is situated in the Nephin Beg range at an approximate elevation of 150 m above sea level and is located within a sub-catchment area of 416.2 ha, of which 176.4 ha is fully forested (Ryder et al., 2011). Three areas were used in the present study (Figure 1): (1) a regenerated riparian peatland buffer (RB), clearfelled four years before the present study (2) a recently clearfelled coniferous forest (CF), clearfelled in February

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2011, and (3) a standing, mature coniferous forest (SF), acting as a study control for the nutrient data and on which no harvesting operations took place. The three areas had a north-westerly aspect and an average slope of 5%, while a third-order stream, which is a tributary to the Altaconey River (classed as 'unpolluted' by the EPA (2011)), flows in a north-easterly direction to the north of the site. When the trees were planted, the land was double mouldboard ploughed, creating furrows and ribbons at 2 m spacing, which are perpendicular to the third-order stream. There is a moderate climate, which is heavily influenced by the proximity of the Atlantic Ocean, with average air temperatures of 13 °C in summer and 4 °C in winter, and a mean annual rainfall of 2000 mm (Rodgers et al., 2010). Blanket peat of varying depth (minimum depth measured, 1 m) down to 2 m covers all areas. The blanket peat has an average gravimetric water content of 85±7%, dry bulk density of approximately 0.1±0.06 g cm^{-3} and a mineral content of approximately 3%. Sand and gravel deposits underlay the peat on top of the Cullydoo formation of Srahmore quartzite and schist, which is a poorly unproductive aquifer (McConnell and Gatley, 2006).

[Figure 1 here]

The site was planted in 1966 as a mixture of Sitka Spruce (*Picea sitchensis (Bong.) Carr.*) and Lodgepole Pine (*Pinus contorta Dougl.*). In May 2006, an area of 2.49 ha 30 m north, 50 m south and 300 m along the river was clearfelled to create the RB (Ryder et al., 2011) (Figure 1, identified as Regenerated Buffer). Bole-only clearfelling was carried out with a harvester and a forwarder with the brash material positioned ahead to create a brash mat on which to drive forward, thus protecting the soil from consolidation. These brash mats remained on site after clearfelling was completed. Typical forest practice

would be to arrange these brash mats into regular rows ('windrowing') away from the watercourse when preparing the site for replanting.

In February 2011, clearfelling of an area of 2.61 ha (1230 m^3) of the forest upslope of the RB area began (identified as 'Clearfell Forest' in Figure 1). Clearfelling was conducted in a similar manner to the RB. The brash mats in this area also remained *in-situ* for the study period. No harvesting took place within the adjacent SF (identified as 'Standing Forest' in Figure 1).

2.2. Measurements conducted using Piezometers

The WT depths and groundwater nutrient concentrations for the present study were measured from May 2010 until December 2012. This allowed for examination of two time periods: (1) from 4 to 6 years after clearfelling within the RB (clearfelled in May 2006) and (2) before (9 months) and after (22 months) harvesting of the CF (clearfelled in February 2011). For discussion and analysis, the CF was divided into pre-clearfell (pre-CF) and post-clearfell (post-CF) periods. In total, 11 piezometers, comprising 4 in the RB and 7 in the CF, were used to measure WT variation and 167 piezometers, comprising 48 in the CF, 54 in the SF and 65 in the RB, were used to measure shallow groundwater concentration

2.2.1. Watertable

To investigate the spatial difference in WT depths, 11 piezometers, each with an internal diameter of 40 mm, and an end pipe screen interval of 0.3 m, which was covered with a

nylon sock, were augured at random locations across two sites (4 piezometers in RB and 7 piezometers in CF; Figure 1). Contact between the peat and the piezometer was ensured by incorporating a sand infill, with the remainder backfilled with bentonite. Average depth of installation was approximately 1 m bgl. A high resolution WT mini-diver (OTT Orpheus Mini, Germany), set to record pressure head and water temperature at 30-min time intervals, was placed at one location in the CF area over the study duration (Figure 1). The remaining 10 piezometers were manually dipped once-a-month with an electronic water dip meter (Model 101, Solinst, Canada).

Rainfall was recorded using a rain gauge (Environmental Measurements Limited, UK) (Figure 1). A number of rainfall events and subsequent fluctuations in WT over the study period were tabulated to determine the response rate of the WT to a rainfall event. This analysis was conducted before and after clearfelling, and included initial WT at the beginning of a dry period, volume and timing of daily rainfall, time lag in recovery from deep WT (to allow elucidation of the recovery time from a deep WT position following rain) and relatively shallow WT (to allow elucidation of the recovery time from a WT position following rain when the peat was already saturated). In total, six events were analysed, three in the pre-CF period and three events post-CF. These events included dry periods, with associated deep WT, and wetter periods with shallow WTs. The dry period and deep WT at the beginning of the monitoring was not analysed because the initial height of the WT before the dry period began was not known.

2.2.2. Shallow groundwater samples

Another set of multi-level piezometers were installed within the CF (48 piezometers; 24 overlain by brash material with a depth of approximately 0.45 m and 24 in a vegetated area overlain by needles and small branches) and SF (54 piezometers, covering a distance from 45 m to 1 m up-gradient of the river) areas to capture the nutrient concentration of the recently recharged water and that of older shallow groundwater migrating slowly through the aquifer in the direction of the groundwater flow. Sixty-five piezometers were also placed in the RB, the results of which are presented in Finnegan et al. (2012). Each sampling location comprised three multilevel piezometers, each with an internal diameter of 0.011 m, installed to depths of 0.2, 0.5 and 1 m bgl. Each piezometer had a screen interval of 0.1 m at its base and was covered with a nylon filter sock. A steel rod was inserted into the piezometer for support at the installation stage, and the tops of the piezometers were covered to prevent the ingress of rain water.

Water samples from the SF and CF areas were collected during episodic storm events from May 2010 to May 2012 (n=8 dates; 3 pre-CF and 5 post-CF). Any water lodged in the bottom of the piezometers was removed under suction the day before water sampling, and the piezometers were allowed to fill overnight. Shallow groundwater samples were filtered immediately using 0.45 µm filters, and were returned to the laboratory and tested the following day. Samples were analysed for (1) dissolved reactive phosphorus (DRP) (2) ammonium-N (NH_4^+-N) (3) NO_3^--N and (4) total oxidised nitrogen (TON). All water samples were tested in accordance with standard methods (APHA, 2005) using a nutrient analyser (Konelab 20; Thermo Clinical Labsystems, Finland).

2.2.3. Statistical analysis

Nutrient data from shallow groundwater piezometers were checked for normality and homogeneity of variance, and then logarithmically transformed before analysis. Data were then analysed using repeated measures ANOVA with Datadesk, with the three management scenarios (riparian buffer, standing forest and clearfelled forest) as treatments and the piezometers as replicates. The analysis was conducted separately for each depth.

3. Results

3.1. Impact of clearfelling on watertable

The WT remained consistently below 0.3 m during the pre-CF period in the CF area. The high resolution WT data within the CF area showed an immediate rise in the WT to within 0.3 m bgl after clearfelling commenced (Figure 2). This rise in WT was despite a lower cumulative rainfall for the time period after clearfelling than for a similar time period before clearfelling (Figure 2). The WT fluctuated seasonally between ground level and 0.3 m bgl in the four piezometers (no. 8 – 11) positioned in the RB, which had been clearfelled four years prior to the present study.

[Figure 2 here]

Minimum, median and maximum depths to WT pre- and post-CF from the high resolution WT diver and the sampling piezometers (with corresponding fluctuations in WT) are shown in Table 1. The minimum depths to WT (bgl) from piezometers in the CF

area were all post-CF, with the exception of piezometer 7, which was closest to the RB (Figure 1).

[Table 1 here]

For both pre- and post-clearfell periods, the interaction between the occurrence of a rainfall event and the subsequent rise in WT was similar: following a prolonged dry period, there would be a time lag between the rainfall event and the eventual rise in WT. This lag was due to the time required to re-saturate the peat. However, following clearfelling, fluctuations in WT were much more pronounced than before clearfelling for similar rainfall events and the lag times were considerably reduced (results not shown).

3.2.   Water quality

The date of sampling (pre- or post-CF) was a significant source of variation for the DRP at 0.2 m bgl under the brash mat in the CF ($p<0.05$). The DRP concentrations measured in the 0.2 m bgl piezometers were significantly higher post-CF under the brash mat in the newly clearfelled forest than elsewhere in the newly clearfelled forest or in the standing forest ($p<0.05$, Figure 3). The higher DRP concentrations, measured in the 0.2 m bgl piezometer under the brash mat in the newly clearfelled forest, indicated DRP leaching from the degrading brash material.

Concentrations of TON were generally similar across all locations sampled, and had a median concentration of 0.12 mg L^{-1} and a maximum concentration of 0.50 mg L^{-1} (results not shown). Similarly, very low values of NO_3^--N (<20 µg L^{-1}) were found across

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all depths and locations throughout the site and were, in many cases, below the limits of detection. Lower concentrations of NH_4^+-N were observed at the 0.2 m depth than at the 1 m depth in both CF and SF areas; however, these differences were not significant (Figure 4).

[Figures 3 and 4 here]

4. Discussion

In the current study, clearfelling caused the WT to rise. Renou and Farrell (2005) propose that such a change was due to a reduction in transpiration from the trees and increased evapotranspiration from the soil. This rise is also in agreement with other studies (Dubé et al., 1995; Pothier et al., 2003; Jacks and Norrström, 2004; Kaila et al., 2012). The much more pronounced fluctuations in WT following clearfelling than before clearfelling may have been due to reduced interception of rainfall by the trees (which were now clearfelled), hysteresis in the peat (Naasz et al., 2008), or increased saturation of the peat with the elevated WT, which meant that it was more responsive to changes, as less time was required to re-saturate the peat following rainfall events.

The presence of NH_4^+-N and low concentrations of NO_3^--N in the aerobic upper peat layers in the current study was most likely due to the nitrification of NH_4^+-N to NO_3^--N. The low levels of NO_3^--N indicated that this process was followed by either further nitrification of NO_3^--N to N_2O or denitrification of NO_3^--N to N_2 or N_2O during occasional water logging of the soil. Jacks and Norrström (2004) also found that more NO_3^- reduction occurred in the upper 0.15 – 0.20 m of peat in forested wetland buffers.

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Marginally higher NH_4^+-N concentrations were present at the 1 m depth, possibly due to the process of DNRA, which is thought to require a nitrate-limited environment with excessive labile carbon (Stark and Richards, 2008), provided here by the organic peat. The elevated NH_4^+-N, coupled with limited NO_3^--N concentrations, indicated that DNRA, as opposed to denitrification (which would have decreased NH_4^+-N concentrations), was occurring at depth (Necpalova et al., 2012). Indeed, the $C:NO_3^-$ ratio, rather than the redox potential of the soil *per se,* is considered to be the principle factor regulating nitrate partitioning between denitrification and DNRA, with $C:NO_3^-$ ratios greater than 12 considered to be required for substantial DNRA (Fazzolari et al., 1998). Dissimilatory nitrate reduction to ammonium, carried out by strictly anaerobic bacteria (Necpalova et al., 2012), results in the production of NH_4^+-N (Scott et al., 2008). This NH_4^+-N is incorporated into the microbial biomass in the peat (Daniels et al., 2012), providing potential long-term attenuation of the pollutant (Fenton et al., 2009). Similar concentrations and patterns in inorganic-N to the current study site (but mostly as NO_3^--N) were observed by Stevens et al. (1995) in a freely draining ferric stagnopodzol, and were attributed to active nitrification in the freely draining soil. In contrast, Titus and Malcolm (1991) found that, due to a lack of nitrification following a rise in the WT after clearfelling, NH_4^+-N dominated the inorganic concentration in shallow groundwater.

Elevated DRP concentrations in the shallow groundwater in the current study were most likely due to the degradation of the forest residue. Dissolved reactive phosphorus leaching from degrading brash material to the underlying soil has been measured in many studies (Stevens et al., 1995; Väänänen et al., 2007; Rodgers et al., 2010; Finnegan et al., 2012). On the same study site, Finnegan et al. (2012) found that DRP concentrations

were significantly higher under 5 year-old brash mats in the RB than in the adjacent SF, showing the degradation of the logging residue and leaching of DRP to the soil following clearfelling. Stevens et al. (1995) found that the brash material from their site in North Wales, which was planted with Sitka spruce, contained 32 kg ha^{-1} of P and 291 kg ha^{-1} of N. After clearfelling, up to 10 kg ha^{-1} of P (within one year after felling) and 14 kg ha^{-1} of inorganic N (within four years of clearfelling), with the majority of this being NH_4^+-N, and was found in the brash throughfall (Stevens et al., 1995). Large amounts of P can be easily released from brash material, but N varies from small releases (approximately 5% of N content of brash material) (Stevens et al., 1995) to no obvious gain or loss (Kaila et al., 2012). This is due to the high C:N ratio of the brash material and subsequent high initial N immobilization as opposed to mineralization (Nieminen, 1998). Stevens et al. (1995) found their brash material was a sink of inorganic-N in the first three years after clearfelling, with values in the brash throughfall lower than that in the rain. Needles contain half-to-two thirds of total nutrients of the brash material and the needle drop time period may occur anywhere from three to nine months following clearfelling, depending on local climate and season (Forest Research, 2009).

5. Conclusion

Clearfelling of a standing forest on blanket peat raised the watertable. Different transformational processes occurred in harvested and standing forest areas, which resulted in different nutrient speciation. An elevated DRP concentration in shallow groundwater was measured under the brash mat in the harvested site, and was likely affected by the decay of the logging residue. Lower NH_4^+-N concentrations were

measured in the upper 0.2 m, possibly due to nitrification, but low NO_3^--N concentrations were also measured, indicating denitrification during periods of shallow WT.

6. Acknowledgements

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Figure Captions

Figure 1: Location of the Altaconey Forest with site instrumentation, within the Burrishoole catchment.

Figure 2. Depth to the WT (m bgl) from the high resolution WT diver (top) and daily rainfall (mm) (middle) from May 2010 – May 2012 in the Altaconey Forest. Cumulative rainfall over the same time period of 277 days pre- and post-CF in the Altaconey forest (bottom). Dashed line indicates start of clearfelling.

Figure 3. Dissolved reactive phosphorus (DRP) (μg L^{-1}) in shallow groundwater at 0.2 m (top), 0.5 m (middle) and 1 m (bottom) depths from the CF area (clearfell forest under brash (CF UB) (n=24) and CF vegetated area (CF VA) (n=24)) and the standing forest (SF) (n=54) over the 2-year study period (May 2010 – May 2012) in the Altaconey Forest. Standard error shown by error bars.

Figure 4. Ammonium (NH_4^--N) (mg L^{-1}) in shallow groundwater at 0.2 m (top), 0.5 m (middle) and 1 m (bottom) depths from the CF area (clearfell forest under brash (CF UB) (n=24) and CF vegetated area (CF VA) (n=24)) and the standing forest (SF) (n=54) over the 2-year study period (May 2010 – May 2012) in the Altaconey Forest. Standard error shown by error bars.
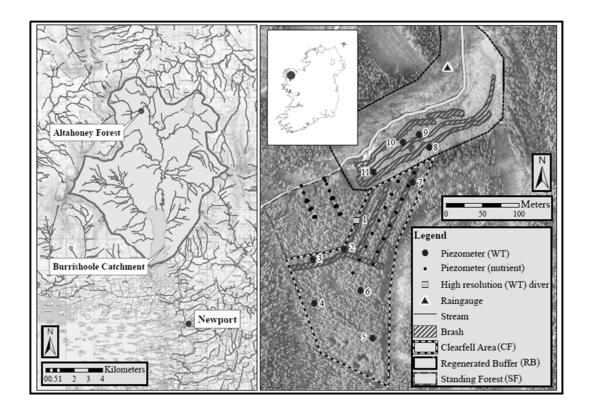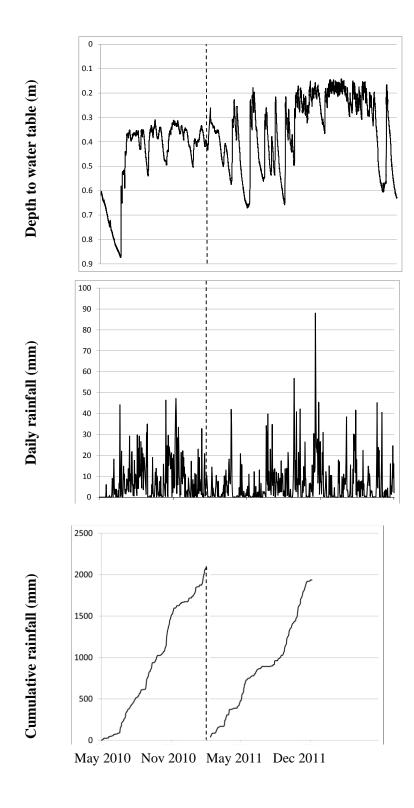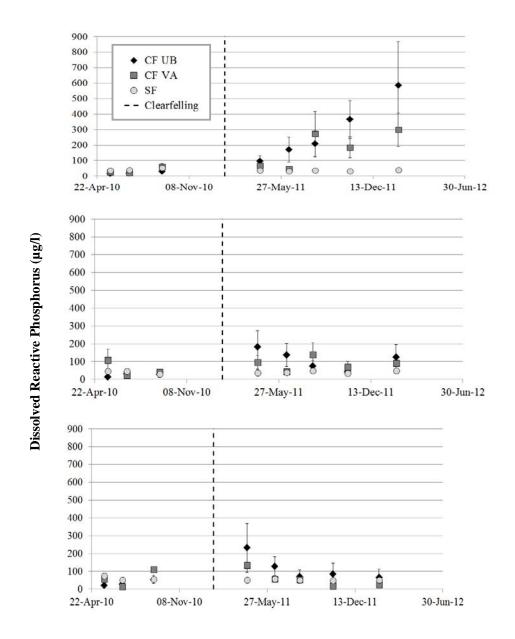
Figure 1

Figure 2.

Figure 3.

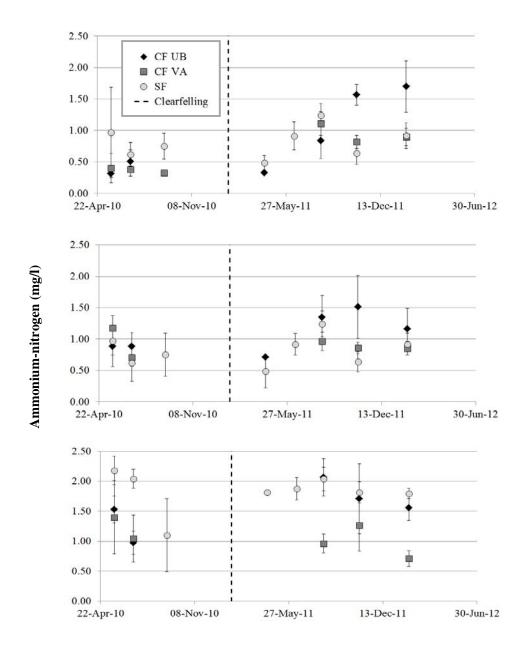The y-axis label reading "Dissolved Reactive Phosphorus (µg/l)" spans all three panels.

Figure 4.

Table 1: Minimum, median and maximum depths (m bgl) to the WT, with subsequent fluctuations in the WT, from the high resolution WT diver (Piezometer no.1) and the sampling piezometers no. 2 – 11 in the RB and the CF for the periods pre- and post-clearfelling over the two and a half year study period (May 2010 – December 2012) in the Altaconey Forest

Piezometer No.	Area	WT depth (m bgl) Pre-CF				WT depth (m bgl) Post-CF			
		Min	Median	Max	Fluctuation	Min	Median	Max	Fluctuation
1*	CF	0.310	0.393	0.872	0.562	0.142	0.312	0.669	0.527
2	CF	0.360	0.389	0.642	0.282	0.335	0.380	0.430	0.095
3	CF	0.435	0.492	0.847	0.412	0.430	0.546	0.680	0.250
4	CF	0.226	0.280	0.605	0.379	0.215	0.238	0.420	0.205
5	CF	0.234	0.469	0.750	0.516	0.133	0.407	0.560	0.427
6	CF	0.210	0.250	0.412	0.202	0.105	0.246	0.280	0.175
7	CF	0.010	0.118	0.195	0.185	0.015	0.052	0.140	0.125
8	RB	0.075	0.104	0.185	0.110	0.048	0.084	0.205	0.157
9	RB	0.000	0.068	0.088	0.088	0.000	0.040	0.140	0.140
10	RB	0.160	0.220	0.270	0.110	0.105	0.175	0.250	0.145
11	RB	0.205	0.238	0.298	0.093	0.194	0.244	0.285	0.091

* high resolution WT diver