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Investigating the effect of historical treatments on wheat yield over multiple spatial frequencies

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Abstract

In this study we use the maximum overlap discrete packet transform (MODWPT) to investigate the impact of historical fertirrigation treatments and cropping on wheat yield. Our objective was to identify the spatial frequencies at which such effects can be detected. Here we consider wheat yield data harvested in consecutive 0.5 m × 0.5 m-sections along the transect. Prior to the wheat crop, a split plot design experiment had been done to investigate the effect of different fertirrigation treatments on melon yield. The wheat transect crossed 9 of the subplots from the melon crop experiment. Each subplot had received a different level of applied nitrogen. The melons were grown at a 1.5 m spacing and will have removed a proportion of the available nitrogen, leaving a soil nitrogen residual. We expect soil properties, such as available nitrogen, to be spatially variable as they result from spatially variable factors operating over multiple orders of spatial frequency. In this example we have good reason to believe this: the applied nitrogen changed from subplot to subplot constituting a low frequency factor, and we expected the removal of nitrogen by the melon crop to be a localized effect in the neighbourhood of the plant therefore constituting a higher frequency factor. We chose to use the MODWPT in this analysis as it is ideally suited to the elucidation of multifrequency processes that are not necessarily stationary in the variance. We show that the applied nitrogen dominates the wheat yield response, and that there is a noticeable contribution to wheat yield variation at the frequency that corresponds to the melon cropping. However the correlation analysis suggests that the relationship between wheat yield and melon positioning is not as straightforward as we might expect and that other influences affect wheat yield variation at this frequency.

1 Introduction

Soil properties are the result of spatially variable factors operating over multiple orders of spatial frequency (here after "frequency"). Soil pH is a good example, at lower frequencies it is likely to be dominated by parent material effects, whereas at higher frequencies patterns of drift and changes in management from field to field will affect it (Milne et al., 2010). We have some knowledge of the size and variability of many factors that influence variability either because they result from human actions, such as fertilizer application, or because we have made measurements that characterize them. If we evaluate the variation (and correlation) of these variables at different frequencies, we are often able understand how the dominant factors that influence the property of interest change with frequency, and quantify their relative importance. In this paper we investigate how wheat yield data reflect known historical treatments of the soil. We need to understand the carry over effects of historical treatments for spatially variable management of nutrients. In particular to see if treatment effects at manageable scales show through and dominate the response of crop yield. Here we show that by decomposing the data into different frequency components we can estimate the variation associated with each treatment and gain an insight their effects.

The data discussed in this paper result from two consecutive experiments done near the Mancha Occidental aquifer (U.H.04.04, 6.953 km^2) and Campo de Montiel aquifer (U.H. 04.06, 3.192 km^2). In the first experiment the effect of different fertirrigation treatments on melon yield were investigated. The treatments comprised three different levels of nitrogen fertilizer and three different levels of irrigation, so in total nine different treatment combinations. The experiment was laid out in a split plot design with irrigation at main plot level and nitrogen-rates replicated in subplots. After the melons were harvested the second experiment was started. Wheat was sown across the plots. No further applications of fertilizer were made and no other experimental treatments applied, so this was in effect a uniform trial. At harvest time a transect was selected that crossed nine former subplots each with a different treatment history. The wheat was harvested in consecutive 0.5 m × 0.5 m-sections along the transect.

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The irrigation water was contaminated with mineral forms of nitrogen (among other things) and so total applied nitrogen for the first experiment was estimated by adding together the fertilizer nitrogen and the nitrogen in the water (which had been measured). This constitutes a known contribution to variation of soil nitrogen at predominantly low frequency (i.e. subplot scale). The melon crop removed a proportion of the nitrogen at a higher spatial frequency dictated by its cropping density. After melon harvest, the use of wheat as a nitrogen sink crop allows us to evaluate the soil nitrogen residual. From melon fertirrigation to wheat harvest, a set of processes influencing the nitrogen cycle have occurred: nitrogen uptake by the melon crop, organic soil nitrogen mineralization, nitrogen lixiviation, horizontal diffusion of soluble nitrogen forms and nitrogen uptake by the wheat crop. Our challenge was to see if these historical treatments were reflected in the yield of the wheat crop. We did not expect the answer to be straightforward as there were other unknown influences on the wheat yield, both unrelated and related to nitrogen. First we investigated the data with some exploratory statistical analysis. Then, because the known influences on nitrogen were strongly frequency-dependent, we investigated the relationship between applied nitrogen, melon cropping and wheat yield using the maximum overlap discrete wavelet packet transform (MODWPT) (see Percival and Walden, 2000).

The MODWPT, as the name suggests, is a development of the discrete wavelet transform. Wavelets were developed in the 1980s for signal processing, and later introduced to soil science by Lark and Webster (1999). Since then they have been applied in several pedological case studies (Lark et al., 2004; Milne et al., 2005; Lark, 2006; Biswas et al., 2008). The MODWPT decomposes a series (whether this be a time series, or as in our case a series of measurements made along a transect) into wavelet packet (WP) coefficients which describe local variation in the series at different frequency intervals, giving up some resolution in space. Wavelet packet coefficients can be used to estimate frequency-specific components of variation and correlation. The former allows us to see which frequencies contribute most to signal variation, and the latter enables us to estimate the correlation between two series across different frequency intervals. This can give us an insight into the dominant processes and how they may relate to a second known variable. In addition, because WP coefficients retain information on the position of features we are able to see if there are any significant changes in variation or correlation across the series, reflecting changes in the dominant process.

2 Material and methods

2.1 Field experiment

The field trials were carried out at La Entresierra field station located in Ciudad Real, central Spain (3°56′ W; 39°0′ N; 640 m altitude) from April 2006 to June 2007, and are described more fully in Castellanos et al. (2010). The soil is classified as Alfisol Xeralf Petrocalcic in the USDA system (Soil Survey Staff, 1999). It overlays fragmented petrocalcic horizon and is shallow in depth, reaching a maximum of 60 cm with very little vertical variation. The soil is sandy-loam in texture, slightly basic (7.9 pH), medium in organic matter (2.2%), rich in potassium (0.9–1.0 mEq L^{-1}, ammonium acetate) and with a medium level of phosphorous (16.4 to 19.4 ppm, Olsen) with ECw. 0.1–0.2 dS m^{-1}.

The area is characterized by a continental Mediterranean climate, with widely fluctuating daily temperatures. In the three years prior to this experiment, non-irrigated winter wheat (*Triticum aestivum L.*) was grown on the plots, to which no organic matter or fertilizers were added.

2.1.1 Melon crop experiment

The melon species used in the experiment was Piel de sapo (*Cucumis melo L.*, var. inodorous, cv. Sancho). This is the most widely cultivated melon in Spain. Seeds were germinated in a greenhouse in April 2006. On 24 May 2006, when they had sprouted two or three real leaves, they were transplanted onto plastic mulch at a density of 4444 plants ha^{-1} (i.e. at 1.5 m spacings). A randomized split plot design was used, with three nitrogen levels and three irrigation levels. Each treatment was replicated four times in subplots measuring between 7.5–16.5 m in width and 12 m length. The subplot widths ranged in size for practical reasons. The plots were arranged on a four by nine grid (see Fig. 1). Each subplot had five, seven or eleven rows of melons, according to its width (melon rows run from top to bottom in Fig. 1).

Each row of melons was drip irrigated, at a rate of 2 l h^{-1}, from a line with emitters spaced at 0.5 m. In order to facilitate the crop establishment, all plots received 30 mm of water immediately after they were transplanted. Following this the irrigation schedule for each treatment was calculated daily. There was no irrigation for the first 14 day. Then every day, for the next 90 days, a single irrigation of 60% (W1), 100% (W2) or 140% (W3) of the melon crop evapotranspiration (E_c) value was applied – see Table 1. Each day crop evapotranspiration (E_c) was calculated following the FAO method (Doorenbos and Pruitt, 1977) given by

$$E_c = K_c E_0 \tag{1}$$

where K_c is the crop coefficient, that was obtained for melon crops previously grown in the same area (Ribas et al., 1995) and E_0 is the reference evapotranspiration calculated using the FAO Penman-Monteith method (Allen et al., 2002). The total irrigation applied was 342.6, 552.9 and 755.9 mm for W1, W2 and W3 respectively. The irrigation water quality was measured weekly to estimate the nitrogen content of the water. The three fertilizer treatment levels include nitrogen, in the form of ammonium nitrate, at doses 0, 150 and 300 kg N ha^{-1}. We denote these levels N0, N1 and N2 respectively. The fertilizer was applied throughout a 10 week period starting in June by mixing it with the irrigation water. As the irrigation water carried some nitrogen, all the treatments add nitrogen to the soil. The total nitrogen applied is shown in Table 1.

The plots were also fertilized with a total of 120 kg ha^{-1} of phosphoric acid over the season. This was added to the irrigation water daily, from three weeks after transplanting until the last week of August. Potassium was not applied due to the large content of this element in the soil. A standard disease- and insect-control programme was implemented throughout the growing period in accordance with usual management practice to ensure that the response to nitrogen fertilizers would not be masked by other factors. Melons were harvested when there was a significant amount of ripe fruit in the field from 26 July to 7 September with a total of seven harvests.

2.1.2 Wheat crop experiment

Winter wheat (*Triticum aestivum* L., cv. Soissons) was grown on the same experimental site as the melon crop discussed above. It was sown on 20 December 2006 in rows spaced 0.15 m apart at a density of 400 seeds m^{-2}. Post-emergence herbicides were used to control weeds. No fertilizer or organic amendments were applied during the season. A transect was selected running perpendicular to the irrigation lines, which went through nine treatment plots (see Fig. 1). On 6 June 2007 the wheat crop was harvested. Each 0.5 m a frame of 0.5 m × 0.5 m was placed on the soil and the wheat plants captured were harvested and placed in labeled bags.

For each sample, wheat grain was separated from the rest of the plant so that we could measure both grain dry-weight and plant dry-weight. These were determined by oven drying at 80 °C to a constant weight. We chose to investigate the scale-dependent relationship between applied nitrogen, melon-position and plant-weight in this study, but we could have equally well chosen to look at grain weight. The two are strongly correlated ($R^2 > 0.96$) so this would have made little difference to our conclusions.

2.2 The wavelet packet transform

There are many good explanations of the MODWPT, most notably Percival and Walden (2000). Therefore we only give a brief description.

If we consider a series of N observations $z(x)$, $x=1,...,N$ made at regularly spaced intervals of x_0. The MODWPT is achieved by convolving the original series $z(x)$, with a subset of the WP filters $\boldsymbol{u}_{j,m}$ where $m=1,...,2^j$ and $j=1,...,J$ where J is a positive integer such that $2^J \leq N$. The filter $\boldsymbol{u}_{j,m}$ retains information on the series from the frequency interval $\left[\frac{m-1}{2^{j+1}x_0}, \frac{m}{2^{j+1}x_0}\right]$, although there is some leakage. It follows that the filters $\boldsymbol{u}_{j,m}$ where $m=1,...,2^j$ decompose the frequency interval $\left[0, \frac{1}{2x_0}\right]$ into 2^j equal intervals, as illustrated in Fig. 2. We call these frequency intervals wavelet packets. Any set of WPs with non-overlapping frequency intervals, which cover the whole frequency interval form a complete WP basis which we can use to decompose the original series. An example of a complete WP basis is illustrated in Fig. 2 by the darker shading.

Each filter $\boldsymbol{u}_{j,m}$ is non-zero for only a small interval length L_j (i.e. $\boldsymbol{u}_{j,m}=\{u_{j,m}(l): l=1,...,L_j\}$), and so when convolved with the original series $z(x)$ results in N WP coefficients given by

$$w_{j,m}(x) = \sum_{i=1}^{L_j} \boldsymbol{u}_{j,m}(i) z(x-i) \quad \text{for } x=1,...,N \,. \tag{2}$$

For this application we padded the series by reflection where the filter overlapped the ends. The wavelet coefficient $w_{j,m}(x)$ can be thought of as a measure of how similar the original series is to the filter $\boldsymbol{u}_{j,m}$ located at position x. In other words, each wavelet coefficient $w_{j,m}(x)$ captures a component of variation local to the nominal position x of the coefficient, and is associated with frequency interval $\left[\frac{m-1}{2^{j+1}x_0}, \frac{m}{2^{j+1}x_0}\right]$.

Percival and Walden (2000) describe how each filter is computed from a mother wavelet filter $\{h_0(l): l=1,...,L\}$ and associated father wavelet filter $\{g_0(l): l=1,...,L\}$,

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where $h_0(l) = (-1)^{l-1} g_0(L-1-l)$. In our analysis we used Daubechies's extremal phase wavelet filter with two vanishing moments (Daubechies, 1992). We selected this wavelet because it has a very compact support (i.e. it takes non-zero values over a narrow interval, $L = 4$, and so is particularly suitable for identifying localized features in the data).

We see from Fig. 2 that with increasing level number j we obtain increased frequency resolution. This is at the expense of resolution in space because the filter length increases with level number, and so the associated wavelet coefficients result from a weighted sum of a larger portion of the original series. The MODWPT basis is generally selected to suit the data by trading resolution in space for resolution in the frequency domain. Usually it is desirable to select a basis that concentrates variance in as few wavelet coefficients as possible (Percival and Walden, 2000; Lark, 2006). This results in good frequency resolution over stationary stretches and good spatial resolution at frequencies with short-range episodic noise. In practice we identify the "best" basis by minimizing a suitable cost function, here we use the cost function proposed by Constantine and Reinhall (2001).

2.2.1 Multiresolution analysis

The MODWPT is invertible which means we can recover the original series from the WP coefficients. A more useful consequence of this is that if we set all coefficients to zero, with the exception of those associated with a given frequency interval (for example $\{w_{j,m}(x) : x = 1, \ldots, N\}$) and then do the reconstruction we obtain the component of the original signal corresponding to that frequency interval. Breaking the signal down into frequency specific components (known as muliresolution analysis – MRA) enables us to visualize the components of variation for each frequency interval. This is often difficult to do from visual inspection of the original series.

2.2.2 The wavelet packet variance and correlation

MODWPT coefficients can be used to estimate the partition of variance between WPs. The variance associated with a particular WP is known as the sample WP variance, and is estimated by

$$\sigma^2_{j,m} = \frac{1}{\hat{N}_j} \sum_{x=a}^{b} w_{j,m}(x)^2 \tag{3}$$

where $\hat{N}_j = b - a + 1$, typically $a = L_j$ and $b = N$ (Percival and Walden, 2000). For short series, such as the one discussed here, these limits can mean that for frequency intervals of interest we discard a large proportion of the WP coefficients in our estimation of WP variance. Therefore we use values of a and b derived by the method described in Milne et al. (2009). Similarly the WP coefficients can be used to estimate WP covariance $C_{j,m}$ between two variables $z(x)$ and $v(x)$. This is given by

$$C_{j,m} = \frac{1}{\hat{N}_j} \sum_{x=a}^{b} w_{j,m,z}(x) w_{j,m,v}(x) \tag{4}$$

where $w_{j,m,z}(x)$ and $w_{j,m,v}(x)$ are the WP coefficients of variables $z(x)$ and $v(x)$ respectively. It follows that the WP correlation $\rho_{j,m}$ is given by

$$\rho_{j,m} = \frac{C_{j,m}}{\sqrt{\sigma^2_{j,m,z}\sigma^2_{j,m,v}}} \tag{5}$$

(see Percival and Walden, 2000 and Milne et al., 2009).

As we explained above, the WP coefficients capture local components of variance at specific frequency intervals, and so we can see also how WP variation changes with location. Milne et al. (2009) describe a method of detecting changes in WP variance at a given frequency, based on a proposal by Whitcher et al. (2000), and testing to see

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if the changes are significant based on a null hypothesis that the data are a realization of a random variable that is stationary in the variance. A similar method can be used to detect significant changes in WP correlation (see Milne et al., 2009).

The MODWPT results are typically discussed in terms of frequency, but sometimes period (the reciprocal of frequency) is a more intuitive way to present results. In the following we use both concepts.

3 Results and discussion

3.1 Exploratory analysis

Figure 3a shows the plant weights for each of the 18 treatments types (fertilizer level × irrigation level × melon occurrence). The mean for each treatment is plotted in Fig. 3b. From the plots we see that the average plant weight increases with increasing fertilizer application.

3.2 The data

Wavelet analysis requires a series of equally spaced values. Measurements of plant weight were made every 0.5 m. A series describing melon plant position at this frequency was constructed by assigning 1 to locations with melons and 0 where there were none. The position of the transect relative to the fertirrigation lines (i.e. perpendicular) meant that fertirrigation occurs at intervals of approximately 1.5 m along the transect, coincidental with the melon plants. However, because the nitrogen and water are easily transported from the sources we assume nitrogen was applied evenly across each plot. Figure 4a shows the applied nitrogen across the transect with melon position indicated by the symbol ∘. Figure 4b shows the plant weight along the transect.

3.3 The best basis

We calculated the "best basis" for plant weight (our variable of central interest), and then used this WP basis in the remainder of the analysis. The best basis is illustrated in Fig. 5. This basis generally favours frequency resolution over spatial resolution, as predominantly the packets are from level 5 and 4. Only the highest frequency packet is not.

3.4 Multiresolution analysis

Figure 6 shows the MRA of plant weight. The components are stacked one upon another from the highest frequency components at the bottom to the lowest at the top. We see that the low frequency reflects the applied nitrogen closely (see Fig. 4a) as do the next two lowest frequency MRA components.

3.5 Wavelet packet variance

The WP variance was estimated for each variable. Figure 7 shows the results. As the frequency interval changes from packet to packet, depending on which level of decomposition it came from, a simple graph of WP variance against frequency can mislead. Therefore we have plotted the WP variance divided by the associated frequency interval against the midpoint of the frequency interval. This quantity is a standardized WP variance for the frequency interval. The largest contribution to WP variance for applied nitrogen is at the lowest frequency interval. After the first three packets WP variation is relatively small. Not surprisingly these first three packets correspond to frequencies less that 0.0625 cycles per observation, which corresponds to an interval of periods of > 8 m. The narrowest subplot width is 7.5 m, so the first three packets correspond to subplot scale variation. The dominant frequencies for melon position WP variation are 0.33–0.36 cycles per observation (interval of periods 1.4–1.5 m, which is the approximate spacing between melon plants), the peak at 0.14–0.19 is likely to be a harmonic

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of this. Interestingly, the largest contributions to WP variance of applied nitrogen and melon position are reflected in the plant weight results. We see that the largest peak in WP variation, like the applied nitrogen WP variance, is at the lowest frequency. This suggests, perhaps not surprisingly, that in this experiment the applied nitrogen is the main reason for the observed variation in wheat weight. There is a smaller but noticeable peak in variation at the 0.34–0.36 frequency interval consistent with the largest WP variance contribution of melon position. This suggests melon position is having a noticeable effect on wheat weight variation.

3.6 Wavelet packet correlation

The WP correlations between applied nitrogen and plant weight (Fig. 8) show that at low frequencies the variables have large correlations (>0.91) which are significantly different from zero (based on the 95% confidence interval). Although not strictly equivalent, this quantifies the observations made above on the MRA. As frequency increases, the correlation becomes weaker and not significantly different from zero. At these higher frequencies there is very little WP variation in applied nitrogen. The little high frequency WP variation present is an artifact resulting from the assumed step change in applied nitrogen between plots. The WP correlation at these high frequencies measures to what degree the artifacts propagated by the edge effects appear in the wheat yield. We found only one significant change in correlation between these two variables. This was in packet 18 at location 26 where correlation went from weakly negative and not significantly different from zero, to 0.48 and significantly different from zero.

Assuming that the melon crop depletes the nitrogen locally, we would expect to see negative correlations between melon position and plant weight at certain scales. The only correlation that is significantly different from zero is negative (−0.5) and is associated with frequency interval 0.31–0.33, i.e. slightly lower than the frequency interval associated with the largest WP variation of melon position (0.33–0.36 cycles per observation). The WP correlations at these intervals are negative but weak (−0.34) and not significantly different from zero. There is a significant change in WP correlation in packet 19 (frequency interval 0.33–0.34 cycles per observation) at location 91. The correlation goes from −0.53 and significantly different from zero to weak positive not significantly different from zero. This means that between locations 1–91 the observed behaviour is consistent with what we expect, and there after it is not. (There is another significant change in correlation in packet 17 but neither correlation is significantly different from zero or shed light on the process).

4 Conclusions

The WP correlation results show that at low frequencies there is a strong relationship between plant weight and applied nitrogen. At higher frequencies there is negligible variation in applied nitrogen and correlation between the two variables is weak.

We might expect melon position to affect plant weight negatively, particularly where nitrogen is limiting. This is because the melon crop will remove nitrogen from the soil reducing that available to the wheat crop. A simple inspection of the raw data shows that the relationship between the two is not that straightforward. The WP correlations between melon position and wheat weight also suggest little or no relationship between the two variables as they are generally weak and not significantly different from zero. However, interestingly there are coincidental peaks in variation at the 0.33–0.36 frequency interval (interval of periods 1.4–1.5 m). This means that there is a source of variation in plant weight that operates at the same frequency as the dominant frequency of variation in melon positioning. We can identify two possible causes (i) melon position does affect plant weight, but that other sources of variation mask the relationship, (ii) the fertirrigation does not diffuse uniformly across each area and so there is more nitrogen available to the wheat crop at locations where melons once grew. In fact it is likely to be a combination of the two which both operate at the same scale but will have opposite effects on plant weight.

The wheat plant weight data can be thought of as a witness of the historical fertirrigation and cropping. We set out to show how the MODWPT can be used to elucidate the frequency dependent processes that affect plant weight. In this instance we were fortunate enough to have information on the factors we believed most likely to affect plant weight and so we were able to convincingly illustrate the power of MODWPT anaylsis.

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Table 1. The treatments applied to the melon crop, reference evapotranspiration E_0 (15 to 104 DAT) and estimated crop evapotranspiration E_c values (15 to 104 DAT), total irrigation (applied irrigation, taking initial establishment irrigation into account, in the different treatments: 60% E_c (W1), 100% E_c (W2) and 140% E_c (W3)) and applied nitrogen information.

Irrigation treatment	Fertilizer treatment	E_0 (mm)	E_c (mm)	Total irrigation (mm)	Total rain (mm)	Total N in irrigation water (kg N ha^{-1})	Total N in fertilizer (kg N ha^{-1})	Total applied N (kg N ha^{-1})
W1	N0	572.12	419.68	342.6	19.50	55.58	0	55.58
	N1						150	205.58
	N2						300	355.58
W2	N0	572.12	419.68	552.9	19.50	92.78	0	92.78
	N1						150	242.78
	N2						300	392.78
W3	N0	572.12	419.68	755.9	19.50	129.46	0	129.46
	N1						150	279.46
	N2						300	429.46

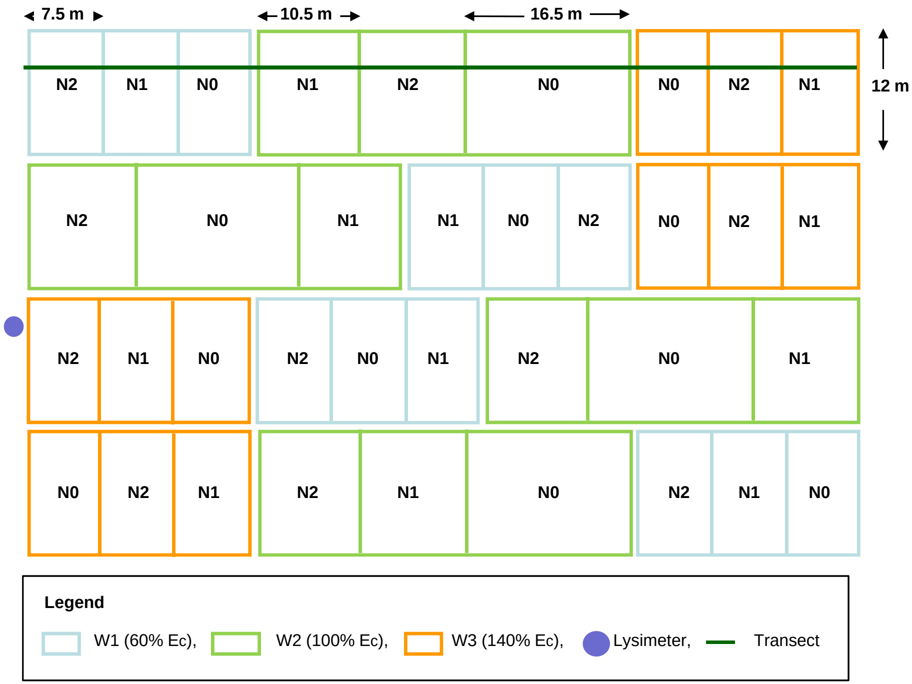

Fig. 1. An illustration of the experimental layout of the melon crop experiment with the wheat experiment transect shown by the dark green line. The fertilizer levels are shown on the figure: N0, N1, N2 represent 0, 150 and 300 kg N ha^{-1} respectively. The three different irrigation levels are indicated by the colour of the subplot lines: light blue is W1, the light green W2, and the orange W3 corresponding to 60%, 100%, and 140% of the estimated crop evapotranspiration (E_c) respectively.

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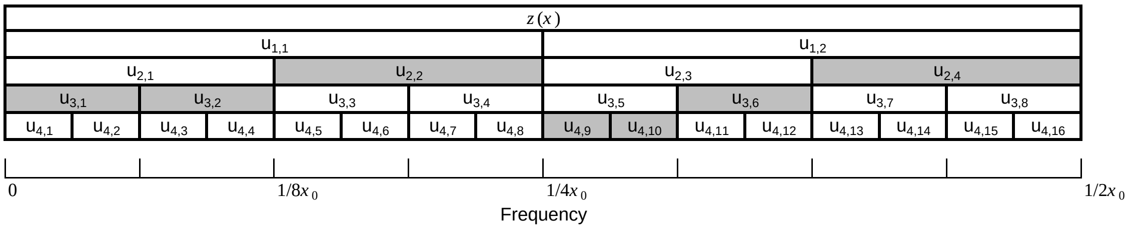

Fig. 2. The MODWPT decomposition of a series $z(x)$, where $x = 1, 2, \ldots, N$ up to level $j = 4$. The nominal frequency ranges associated with each WP filter $\boldsymbol{u}_{j,m}$ are shown. The darker shaded wavelet packets are an example of a complete basis.

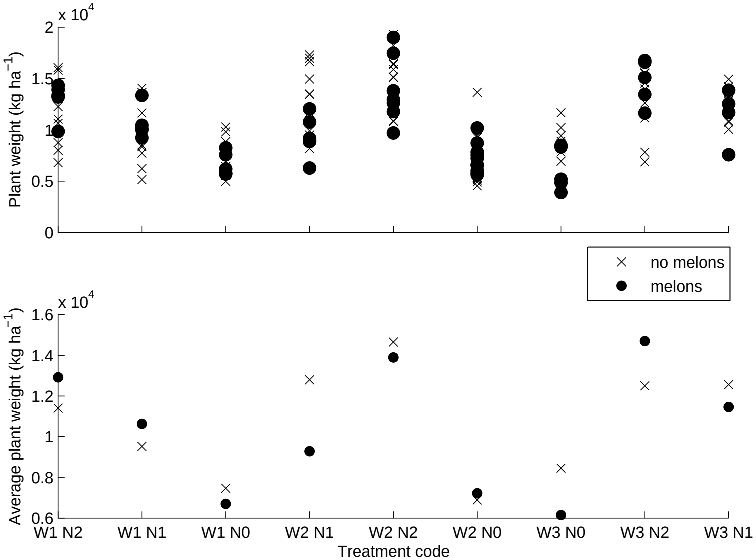

Fig. 3. **(a)** Plant weight (kg ha^{-1}) from locations where melons once grew (•) and where they did not (×) plotted against fertirrigation treatment type, and **(b)** the mean for each treatment plotted against treatment type. Treatment types were as follows. Total irrigation levels of 342.6, 552.9 and 755.9 mm are denoted W1, W2, and W3 respectively. Fertilizer treatments of 0, 150 and 300 kg ha^{-1} are denoted N0, N1 and N2 respectively.

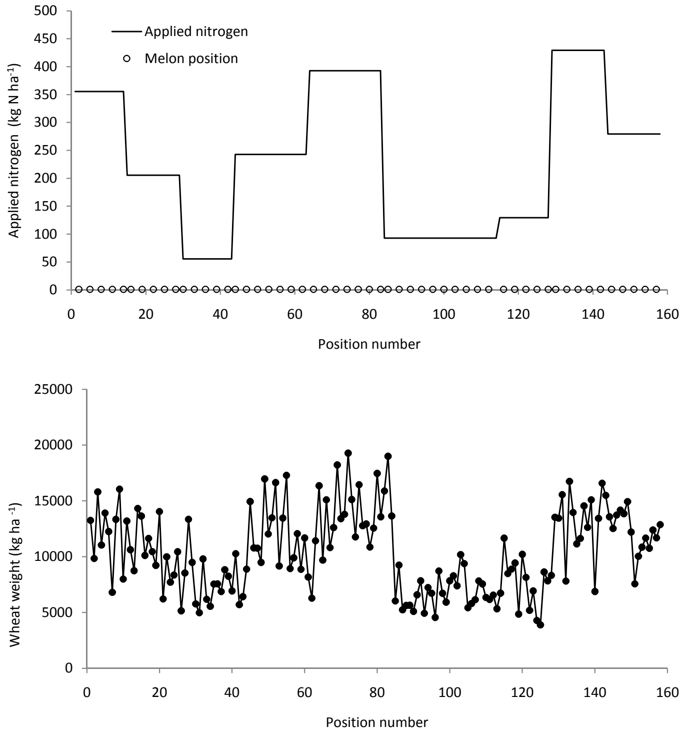

Fig. 4. (a) Applied nitrogen (kg N ha^{-1}) plotted against position. The location of the melon rows are shown by the symbol o. **(b)** The wheat plant weight (kg ha^{-1}) plotted against position.

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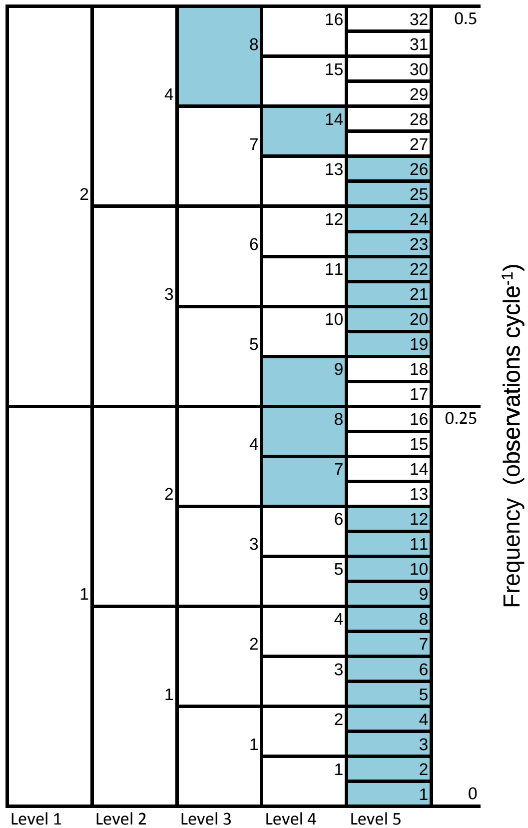

Fig. 5. The "best bases" for plant weight. The nominal partition of the frequency interval by the MODWPT to level 5 is shown with the best bases indicated by the shading. Packet associated with filter $\boldsymbol{u}_{k,m}$ is identified by level number k on the bottom of the grid, and packet number m in the cell.

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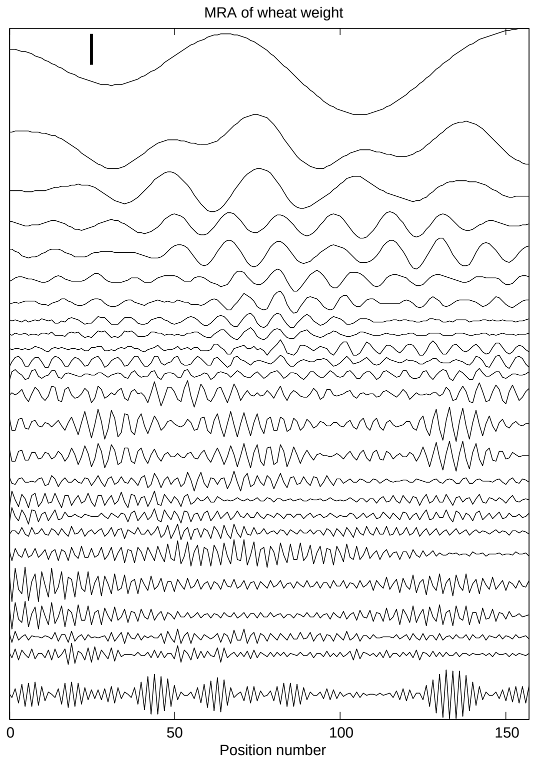

Fig. 6. Multiresolution analyses of wheat plant weight decomposed on the "best basis". The components are stacked from highest frequency at the bottom to lowest frequency at the top (residual once other components are removed). The scale-bar is shown by the vertical bar on the plot and this is of length 50 kg ha^{-1}.

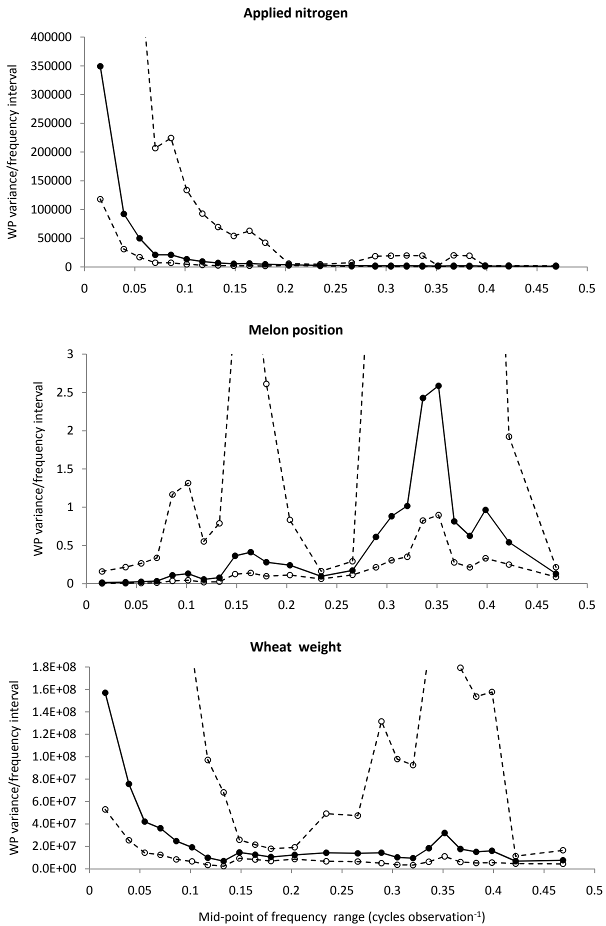

Fig. 7. Standardized WP variances for **(a)** applied nitrogen, **(b)** melon position and **(c)** wheat plant weight plotted against the mid-point of the corresponding frequency interval.

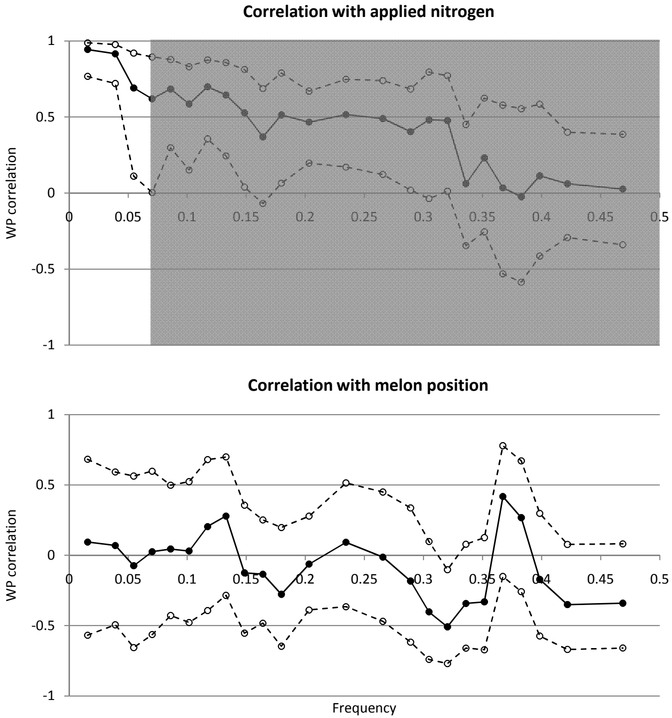

Fig. 8. Wavelet packet correlations between **(a)** applied nitrogen and wheat plant weight, and **(b)** melon position and wheat plant weight plotted against the mid-point of the corresponding frequency interval. In (a) the WP correlations at frequencies larger than 0.0625 are greyed out because there is negligible variation in applied nitrogen at these higher frequency packets (as can be seen in Fig. 7).