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Impact of wind on litterfall in a coniferous forest of southern Sweden

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Abstract

This thesis analyses relationships between the litterfall components needles, twigs, flowers, fruits, and total litterfall and climate variables (wind speed, air temperature, relative humidity, and precipitation) in a coniferous forest located in southern Sweden. Needles, twigs, and total litterfall were positively correlated with daily average as well as maximum wind speed, whereas negatively correlated with daily average temperature. Some months had higher than expected litterfall (03/2021, 01/2022, and 11/2022), and possible reasons include the storm Malik (01/2022) and two heavy snowfall occasions (03/2021 and 11/2022) that hit southern Sweden at those times. Due to the complicated interactions between environmental variables and their interconnected impacts on litterfall, it is unrealistic to firmly state that wind speed is the dominant driver for litterfall. Other variables such as solar radiation, cloud cover, soil water availability, topography, and vegetation structure should be investigated in the future to achieve a broader understanding of the response of litterfall mass to different variables or to a particular event of external disturbances (storm, snow, drought).

Key Words: litterfall, wind, coniferous forest, storm

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Introduction

The prevalence of extreme weather is increasing on a global scale due to climate change (Pourmokhtari, 2022). Being one of the most influential extreme weathers, storms are associated with floods, landslides, human injuries, closure of public transportation, and forest damages. According to the Sixth Assessment Report published by IPCC (2021), storm tracks of extratropical cyclone have shifted poleward in both hemispheres and intense storm events will occur more frequently in a changing climate. It's even claimed that the intensity of extratropical cyclones is underestimated by using the current climate models (e.g.: CMIP5 and CMIP6) due to their coarse resolutions (Seneviratne, 2021). Moreover, the maximum precipitation associated with extreme storm events is predicted to increase with further warming, which might in turn deteriorate heavy precipitation and floods. Severe wind events also bring about disturbances in the forest ecosystem.

As stated by Lindroth et al. (2009), wind-throw by storms can reduce aboveground stocks and assimilation capacity, regionally decreasing terrestrial carbon sink. Apart from negative effects on carbon balance, wind damage in forests are responsible for reduction on tree growth rates and needle productions, destroying the inner structure of branches (Portillo-Estrada et al., 2013). This results in alterations to the dynamics and total mass of litterfall (Lodge et al., 1991). Litterfall is defined as the amount of plant components that drops to the ground per unit time and area (Facelli, 1991). Needles contributes substantially to litterfall in forests, while woody material (i.e.: twigs, barks, branches) together with reproductive fractions (i.e.: flowers, fruits) covering the remaining part (Marod et al., 2023). Litterfall has major implications on carbon balance as a significant component of net primary production.

A previous research (Neumann et al., 2018) analyzed 1604 annual litterfall observations of European forests, declaring that their annual mean carbon input of 224gC/m^2 is equivalent to 36% of net primary production in north Europe and 32 % of that in central Europe. This is similar to global estimations, indicating that litterfall returns a third of the annual carbon uptake back to the edaphic community in forest ecosystems (Grace, 2004). Among various carbon fluxes inside a forest, most of the aboveground organic carbon flux reaching the soil as canopy litterfall (Dai et al., 2023). Acting as a bridge between the aboveground organic matter from plants and the belowground soil organic carbon stock, litterfall plays a crucial role in soil fertility maintenance. Moreover, litterfall supplies 90% of phosphorous and nitrogen absorbed by vegetation (Chapin et al., 2011). Growing trees require nutrition supply from the ground, absorbing elements such as phosphorous, potassium, nitrogen, and carbon through the decomposed litterfall (Spohn, 2023). All combined, litterfall is indispensable to the function and dynamics of forest.

Despite its importance, litterfall is a poorly studied topic. Most studies on litterfall have focused on how it would be affected by temperature (Barlow et al., 2007), precipitation (Campanella & Bertiller, 2010), relative humidity (Zheng et al., 2005), cloud covers (Wagner et al., 2016), solar radiation (Zalamea & González, 2008), or combined effects of several climatic variables (Saarsalmi et al., 2007), while few have studied specifically on wind speed (Kamruzzaman et al., 2013, Marod et al., 2023, Morffi-Mestre et al., 2020, Qiu et al., 2023, Souza et al., 2019), although the latter can cause major input to the litterfall (Lindroth et al., 2009). Taking the "Gudrun" storm that hit southern Sweden in January 2005 as an example, the maximum wind gust reached 35m/s and broke the highest record (Alexandersson, 2005). In total, the storm knocked down nearly 66 million m^3 of trees, which was equivalent to Swedish annual harvest for stem wood (Skogsstyrelsen, 2005).

Among the few studies that have mentioned both wind speed and litterfall, none of them were conducted in north Europe. Litterfall has been found to be positively correlated with wind speed in a tropical dry forest of Mexico (Morffi-Mestre et al., 2020), in a tropical forest of China (Qiu et al., 2023), in a tropical evergreen forest of Thailand (Marod et al., 2023), on a tropical island of Japan (Kamruzzaman et al., 2013), in a mangrove of the Amazon (Souza et al., 2019). However, due to a lack of quantitative data describing litterfall mass and variations among years, long-term investigations of the relationship between a specific climatic variable and litterfall dynamics in evergreen forests are scarce in Europe. It thus remains unclear how wind and its extreme version of storms contribute to litterfall. Such information is essential to monitor the response of forests to climate change and to guide the modelling of soil nutrient levels (Marod et al., 2023).

In this study, I examine the impact of wind speed on litterfall mass in a coniferous forest of Sweden. The main aim is to investigate relationships between wind speed and litterfall for different litterfall fractions, including needles, twigs, fruits, and flowers. Other objectives encompass examining the phenology of different litterfall components and comparing the impact of wind speed with other climate variables (i.e.: temperature, relative humidity, precipitation) on the litterfall. Temperature and precipitation are chosen since low temperature and intense rainfall could promote litterfall. Relative humidity is chosen as a supplementary variable because previous articles have found it significantly correlated with litterfall in Mexico (Morffi-Mestre et al., 2020) and in Thailand (Marod et al., 2023). Low relative humidity increases evapotranspiration and water stress in trees, resulting in earlier senescence and abscission of leaves. This could increase litterfall in forests. It is hypothesized that the litterfall is positively correlated to wind speed because this has been testified in other part of the world as mentioned in the last paragraph. Since storms and gusts could occur frequently in Sweden, wind speed rather than temperature, relative humidity, and precipitation is expected to have a stronger influence on the litterfall.

Method

2.1 Study Area

Being established in 2014, the Hyltemossa site serves as a combined atmosphere and ecosystem research station which involves Integrated Carbon Observation System (ICOS) activities run by Lund University. Located in northwestern Scania (56.0976°N 13.4189°E), the study area is categorized as a warm-summer humid continental climate (Köppen class: Dfb). The average annual temperature, average annual precipitation, and average annual incoming solar radiation of Hyltemossa are 7.4°C, 707mm, and 110$Wm^{-2}s^{-1}$ respectively. Soil type vary from Cambisol with a shallow organic horizon to Podsol. Due to the underlying quaternary deposits, the bedrock mostly comprises Granite which is an acidic intrusion rock and Gabbro which is an ultrabasic rock (ICOS, 2024). The coniferous forest in Hyltemossa includes 3 tree species, with a tree density of approximately 611 trees/ha (ICOS, 2024). The dominant species is *Picea Abies L.* (Norway spruce), currently taking up 97.7% of the total. The remaining small fraction is composed of *Betula pendula Roth.* (birch) and limited occurrence of *Pinus sylvestris L.* (Scots pine). The forest is managed with a turnover rate of 50 years and an estimated growth rate of 34 meters per century (ICOS, 2024). After being damaged by a storm in 1981 and clear-cut in 1982, 3300 trees/ha were replanted (ICOS, 2024). Cleaning of unwanted species was implemented in 1998 and 2005, which was followed by two thinning activities of the existed species with four years interval each. Nowadays, Hyltemossa includes: one 35-year-old and one 40-year-old stand (ICOS, 2018).

2.2 Data

During 2017 to 2023, climate data at height of 30m aboveground were recorded at the Hyltemossa meteorological station. Wind speed as well as temperature and humidity were measured hourly with a sonic anemometer (Metek – uSonic-3 Omni) and a meteorology probe (Rotronic – MP102H), respectively. Datasets of wind speed (m/s), air temperature (°C), relative humidity (%), and precipitation (mm) were downloaded from the ICOS data portal (Heliasz, 2023).

Samples of litterfall amounts were collected by ICOS from 02/2019 to 12/2022. The sampling sites for litterfall are located in the 35-year-old stand. Litter biomass was measured in irregular time interval, ranging from zero to three times per month. Following the *Instruction on Ancillary Vegetation Measurements in Forest* (Gielen, 2017), 20 litter traps were installed in four circular continuous measurement plots (CP), where five locations positioning in a cross-like design within each of the four plots (Figure 1) (Gielen, 2017). Each litterfall trap has a size of 1m^2, being installed approximately 1.2m above ground. The sampled litterfall were subdivided into needles, twigs, flowers, fruits, and others. They were then oven-dried separately at 70°C until reaching constant weights. Finally, cumulative dry biomass for each component was rounded to 0.01g and recorded in gm^{-2} (Gielen, 2017).

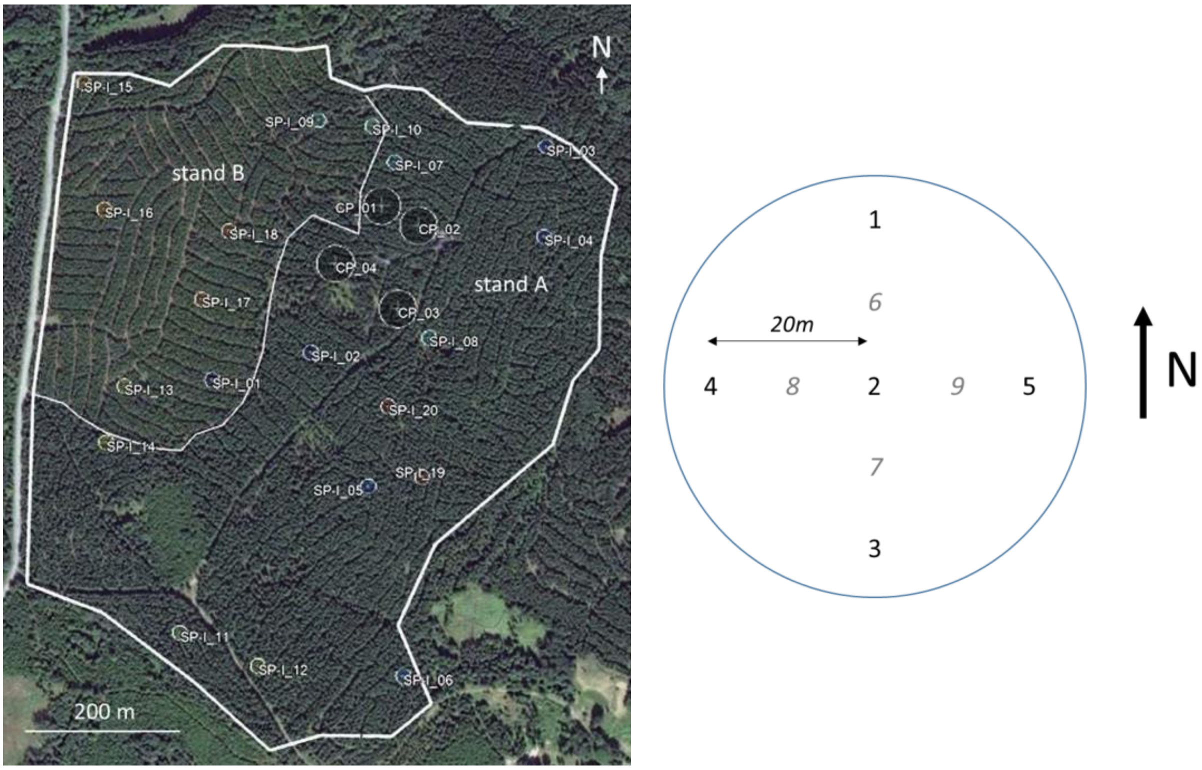


Figure 1: a) Locations of 4 continuous measurement plots (i.e.: CP_01 –CP_ 04) at Hyltemossa research station (ICOS, 2024). b) Schematic diagram of the positions of 5 sampling points inside each CP (Gielen, 2017).

2.3 Statistical Analysis

For each measurement date, total amounts of each litterfall component were summed up. Due to the irregular time interval, total values in gm^{-2} were converted to daily sums by dividing by the number of days between two adjacent sampling dates. This resulted in 71 values for each litterfall component in $gm^{-2}day^{-1}$.

As for the climate variables, the average and maximum values of wind speed (WS), air temperature (T_a), and relative humidity (RH) between two adjacent litterfall measurement dates were calculated. Values between two adjacent litterfall measurement dates were summed up with regard to the precipitation variable (P). Therefore, each computed value served as a stage representation of wind speed or air temperature or relative humidity or precipitation between two sampling dates.

After that, the relationships between the daily dry biomass of the litterfall components (needles, twigs, fruits, flowers, total) and each climate variables (WS, T_a, RH, P) were analyzed with Pearson correlations. Scatter plots with climatic variables and litterfall components including ordinary least square linear regressions were then generated for the relationships that were statistically significantly correlated. The derived linear regression models are only for recognizing residuals and visualizing correlations rather than predicting the further variation of litterfall amounts in accordance with climatic variables. All statistical analysis were done in IBM SPSS Statistics (Version 29.0.2.0).

Results

3.1 Meteorological conditions at Hyltemossa from 2019 to 2022

The maximum wind speed for each measurement period varied from the lowest value of 4.11ms^{-1} in 09/2022 to the highest of 11.7ms^{-1} in 03/2020 (Figure 2a). The following highest values of 10.78ms^{-1} and 10.77ms^{-1} occurred both in 01/2022. In 03/2019, the maximum wind speed also slightly exceeded 10ms^{-1}. Whereas the average wind speed fluctuated in the range of 2.04ms^{-1} to 4.28ms^{-1}, with three times going beyond 4ms^{-1} in 01/2022, 02/2020, and 04/2021. Moving on, the variation of temperature features an oscillatory pattern (Figure 2b), which is characterized by occurrences of high temperature values in summer and low temperature values in winter as well as early spring. The average temperature during the four-years period oscillated between 0°C and 20°C, with 07/2021 and 08/2022 reaching 20°C. Compare with 2019 and 2020, year 2021 and 2022 had colder winter, where the mean temperature dropped below 3°C for the first three months of the years. As for the maximum temperature, it reveals that there has been a gradual rise in the first half of the year and a steady decline in the second half of the year, with all years peaked at summertime for over 30°C. Except from the first half-year of 2021, in which the temperature fluctuated from month to month, yet conforming the overall increasing trend. The average relative humidity varied from 47% in 04/2021 to 98% in 12/2022 (Figure 2c). Overall, above average relative humidity appeared during autumn and winter whereas below average relative humidity dominated the rest of the year. This can be evidenced by the fact that the lowest average relative humidity of each year all took place in April, which never had exceeded 70%. Additionally, maximum relative humidity is not shown in the figure because of its nearly constant value of 100%. The precipitation was generally higher in autumn and winter than in spring and summer (Figure 2d). It peak in 09/2019 with 194.8mm, which was followed by 179.1mm in 02/2020. Other values above 100mm occurred in January, February, March, September, or October. Compared with previous three years, 2022 received less precipitation.

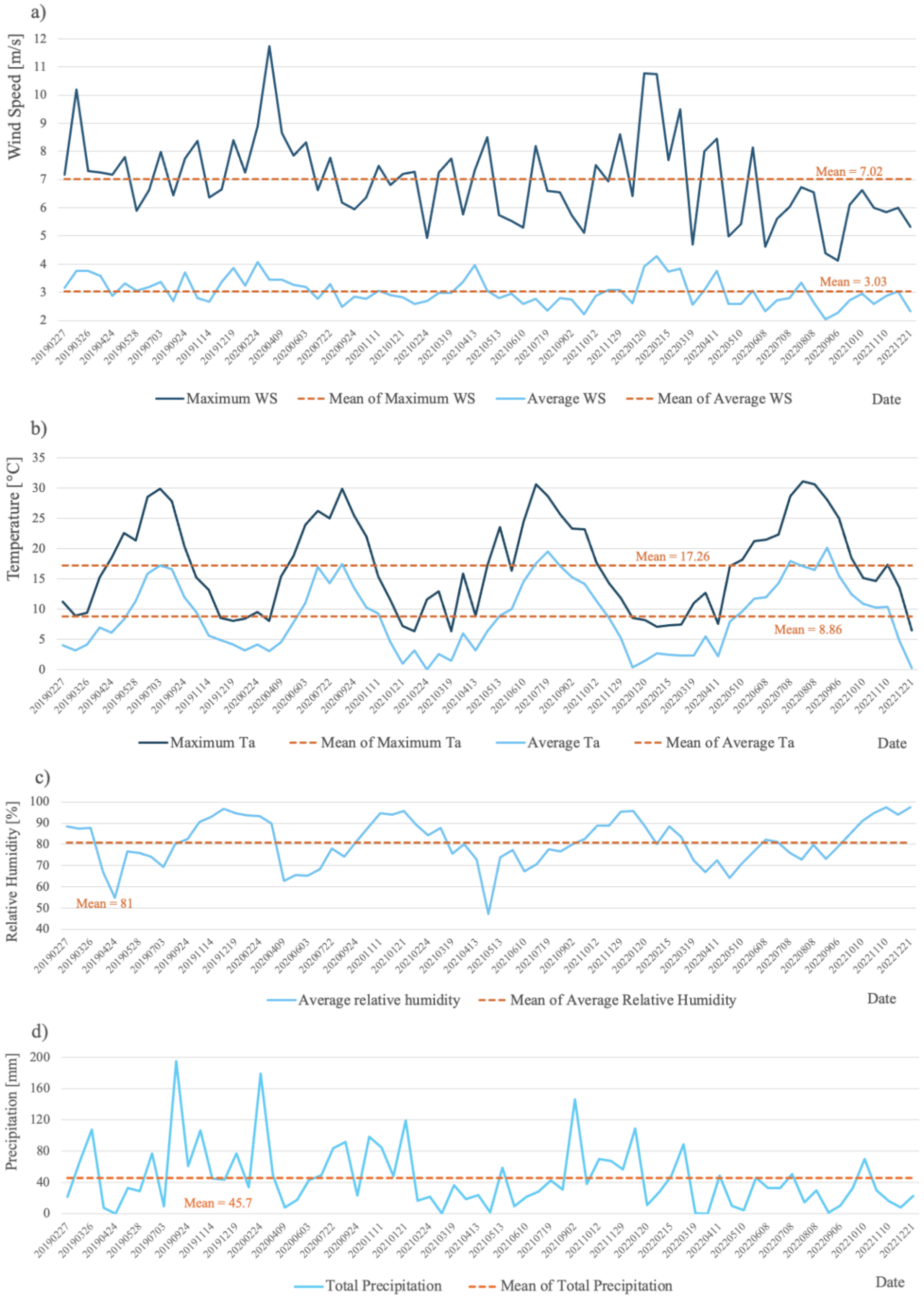
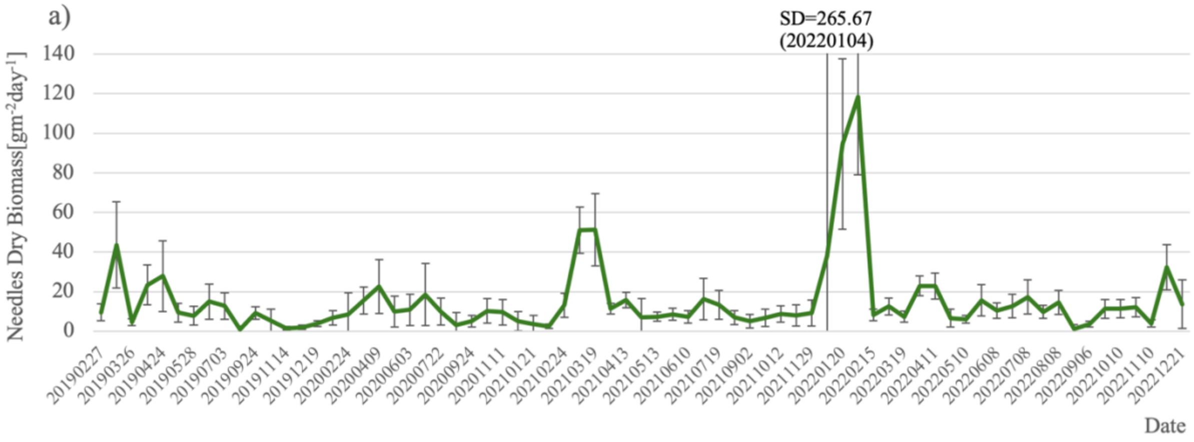


Figure 2: Variation over time for a) wind speed b) temperature c)relative humidity d) precipitation from 02/2019 to 12/2022

3.2 Litterfall at Hyltemossa from 2019 to 2022

The daily sums of litterfall of needles undulated within the range of 0.99 – 51.23$gm^{-2}day^{-1}$, except in 01/2022 where the two measurements peaked at 94.52$gm^{-2}day^{-1}$ and 118.48$gm^{-2}day^{-1}$ (Figure 3a). Furthermore, values higher than 20$gm^{-2}day^{-1}$ mostly occurred in March or April, with one exception in 11/2022. Among the crests, needles litterfall surpassed 40$gm^{-2}day^{-1}$ once in 03/2019 and two times in 03/2021. The standard deviations varied from 0.88 – 42.97$gm^{-2}day^{-1}$, with an outlier being 265.67$gm^{-2}day^{-1}$ on 04/01/2022. Moving onto twigs (Figure 3b), the litterfall amount varied between 0.06$gm^{-2}day^{-1}$ and 9.18$gm^{-2}day^{-1}$ during most of the time. Similar to the needles, value of twigs also experienced a sharp rise in 01/2022, reaching 39.77$gm^{-2}day^{-1}$, 15.02$gm^{-2}day^{-1}$, and 38.09$gm^{-2}day^{-1}$ with a mean of 30.96$gm^{-2}day^{-1}$. Apart from this, twigs litterfall was only higher than 5$gm^{-2}day^{-1}$ in 03/2019, 04/2019, 03/2020, and 04/2022. The appearance of higher values in March and April was in accordance with needles litterfall. Standard deviations for twigs were in general in the range of 0.11-14.56$gm^{-2}day^{-1}$ with an outlier of 165.6$gm^{-2}day^{-1}$ also appearing on 04/01/2022. Compared to needles and twigs, fruits and flowers took up a much smaller proportion of the total litterfall amount. For the fruits, 56 of the total 71 measurements were lower than 1$gm^{-2}day^{-1}$ (Figure 3c). Among which, 31 samplings contained no fruits inside. The highest values appeared in 2020 and the first part of 2021, with 09/2020 and 04/2021 almost reaching 10$gm^{-2}day^{-1}$. Likewise, litterfall of flowers were lower than 1$gm^{-2}day^{-1}$ in 61 out of 71 measurements, and eight of which were zero. Yet, it can be seen that flowers tended to fall in June and July (Figure 3d). All combined, the total non-woody litterfall varied in a similar pattern to needles and twigs (Figure 3e). The peak occurred in 01/2022, where the three total measurements were 77.94$gm^{-2}day^{-1}$, 109.7$gm^{-2}day^{-1}$, and 159.29$gm^{-2}day^{-1}$. This resulted in an average of 115.64$gm^{-2}day^{-1}$ total litterfall in 01/2022. The succedent top values were observed in 03/2021, in which the two measurements were 51.85$gm^{-2}day^{-1}$ and 60.81$gm^{-2}day^{-1}$. This was followed by 49.48$gm^{-2}day^{-1}$ in 03/2019 for the summed litterfall amount.



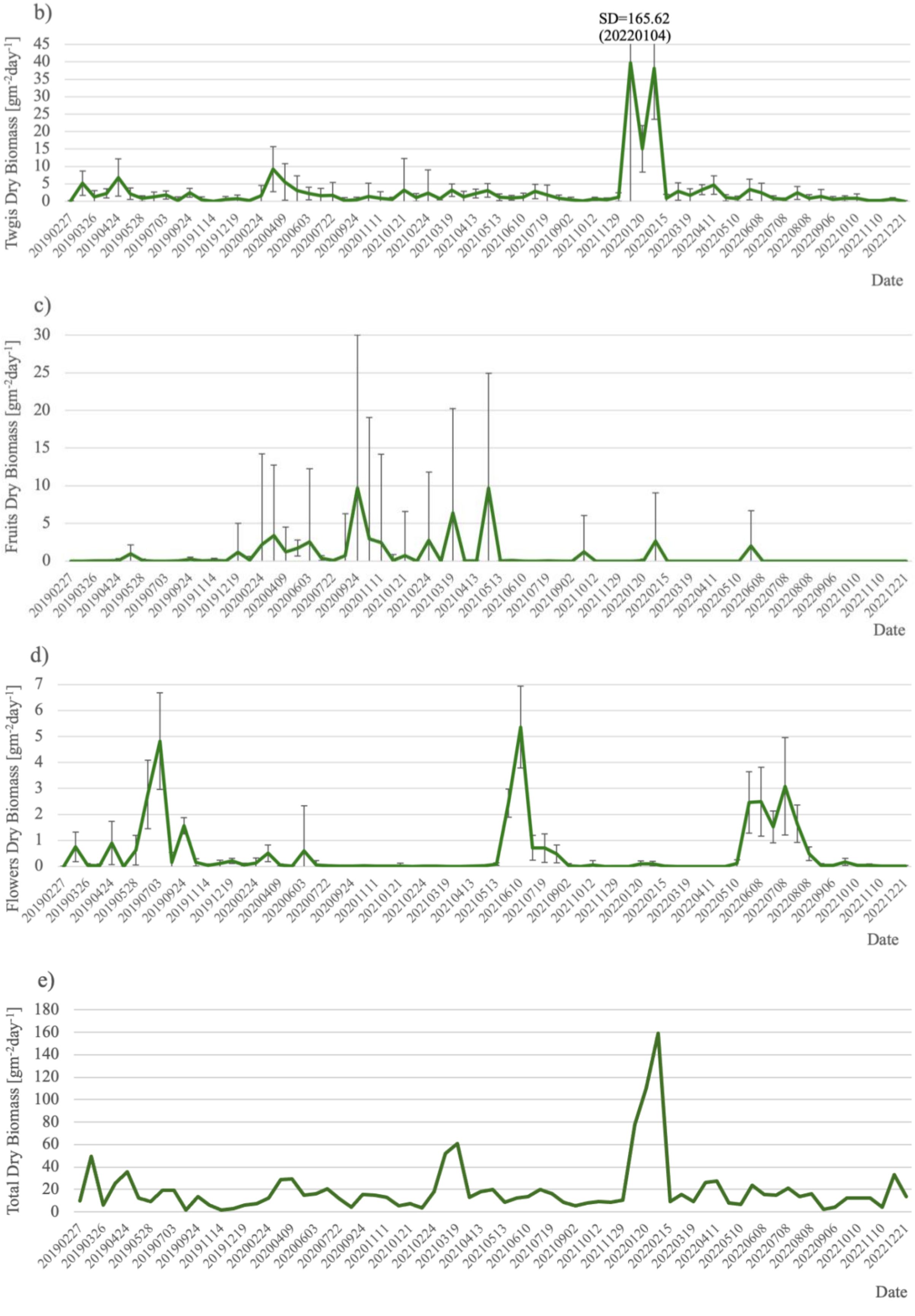
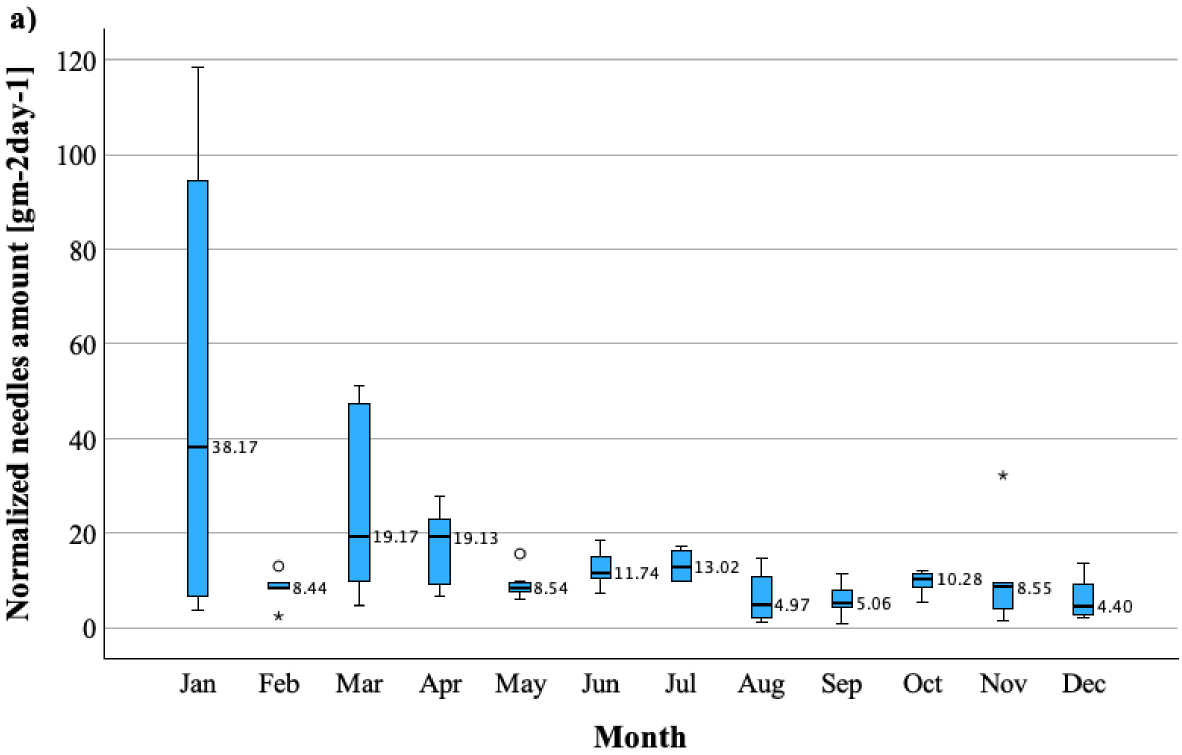
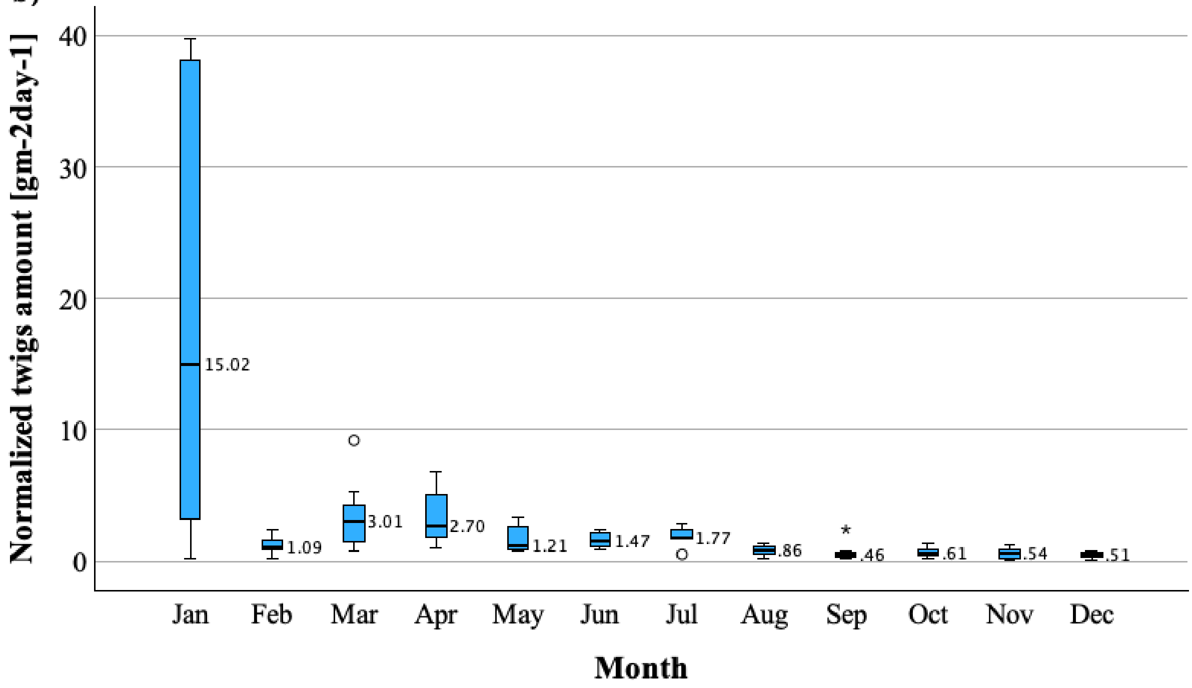


Figure 3: Variation over time for normalized daily litterfall amount against the corresponding measurement date, with fractions of: a) needles, b) twigs, c) fruits, d) flowers, and e) all components. Error bars present standard deviations of the 20 measurements on the same date.

The phenological pattern of needles litterfall indicated that the highest dry biomass amount of this component occurred in January, with a median of 38.17gm^{-2}day^{-1} (Figure 4a). The median values for the rest of months were all below 20gm^{-2}day^{-1}. March and April had the second and third largest needles litterfall collection, in which the medians were both about half of that in January. The lowest median took place in December, which was 4.4gm^{-2}day^{-1}. The general phenological pattern of twigs was similar to that of needles (Figure 4b). Among the twelve months, January had the largest twigs litterfall, which was followed by March and April. When compared between seasons, twigs litterfall appeared the lowest during the autumn months. As for fruits litterfall, the median values were constantly below 0.2gm^{-2}day^{-1}, among which eight months were completely zero (Figure 4c). A clear phenology of flowers litterfall was also seen, with the values peaked during summertime and late spring (Figure 4d). Yet flowers litterfall were almost absent in other period of a year. Adding up all these four components, Figure 5e shows an identical trend to that of needles and twigs litterfall. The total amount of litterfall was dominant in January with a median of 78gm^{-2}day^{-1}. The succedent median values were 27gm^{-2}day^{-1} and 23gm^{-2}day^{-1}, which showed up in March and April, respectively.



b)


Normalized twigs amount [gm-2day-1]
40
30
20
10
0
15.02
1.09
3.01
2.70
1.21
1.47
1.77
.86
.46
.61
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Jun
Jul
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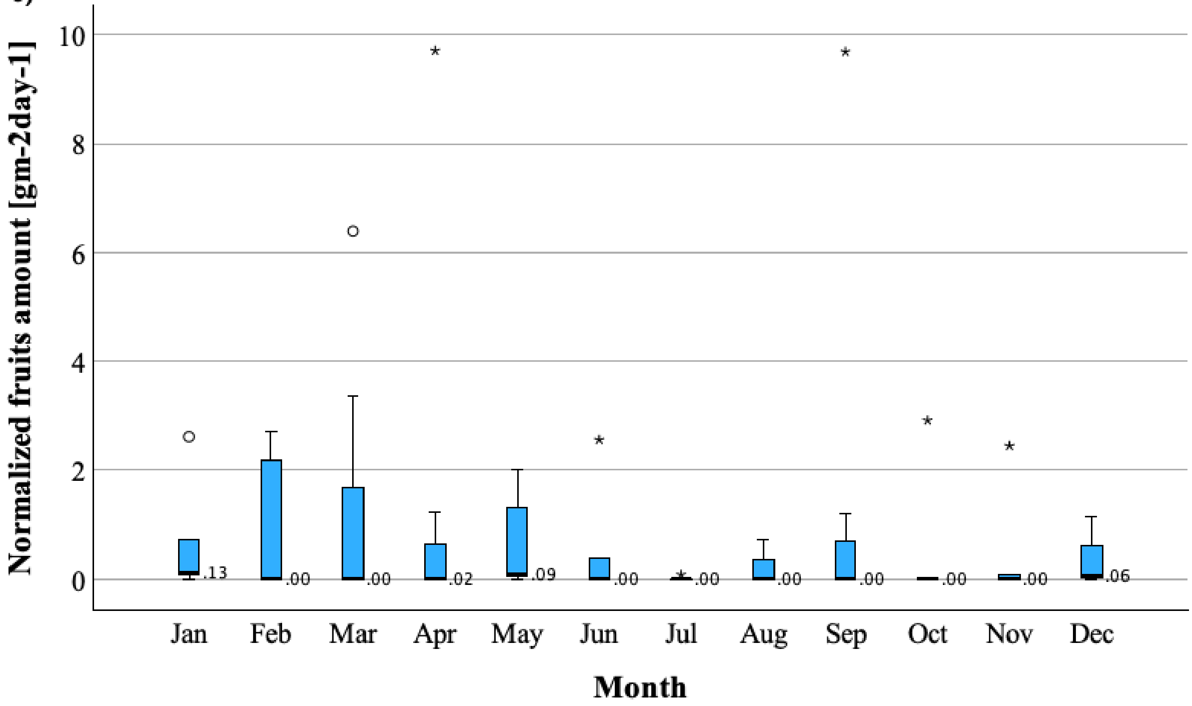
Nov
Dec
Month

c)


Normalized fruits amount [gm-2day-1]
10
8
6
4
2
0
.13
.00
.00
.02
.09
.00
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.00
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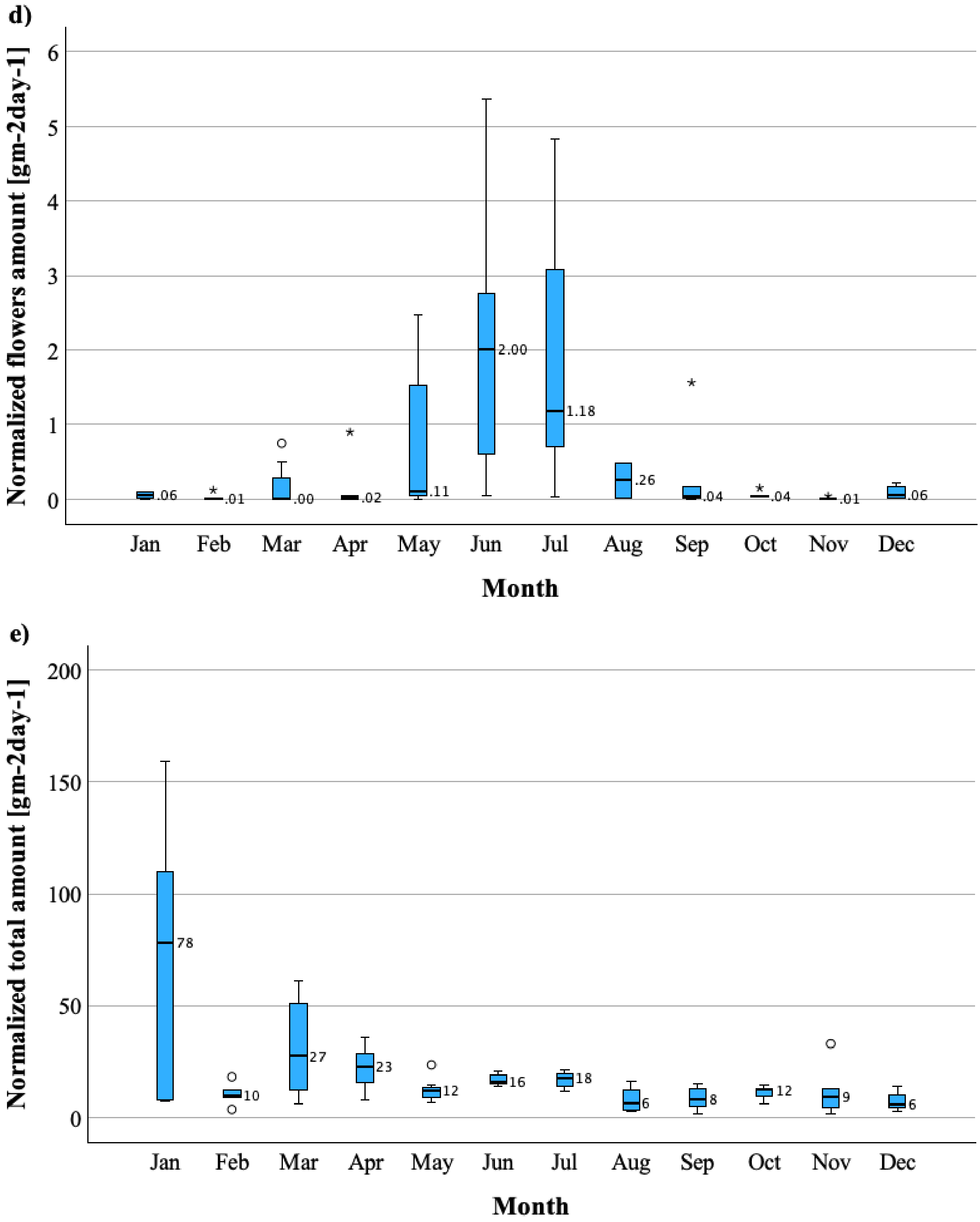

Figure 4: Box plots showing phenology of different components: a) needles, b) twigs, c) fruits, d) flowers, e) all components. Dots are outliers, which is defined as cases lying more than 1.5 box-lengths outside the box. Asterisks are extreme outliers, lying more than 3 box-lengths outside the box.

3.3 Relationships between litterfall components and climate variables

Table 1: Pearson correlation coefficients (r) between climatic variables and litterfall fractions, where moderate to strong correlation (r > 0.4) are in red. Double asterisks (**) indicates that the correlation is significant at the 0.01 level (two-tailed).

	Average Wind Speed	Maximum Wind Speed	Average Air Temperature	Maximum Temperature	Average Relative Humidity	Total Precipitation
Needles	0.409**	0.493**	-0.337**	-0.303	-0.014	-0.186
Twigs	0.269**	0.370**	-0.315**	-0.279	0.037	0.037
Total	0.396**	0.496**	-0.339**	-0.296	-0.030	-0.049
Flowers	-0.049	-0.097	0.415**	0.423**	-0.269	-0.127
Fruits	0.074	0.204	-0.108	-0.038	-0.220	-0.144

As presented in Table 1, litterfall dry biomass of needles, twigs, and all components combined are statistically significantly correlated to climatic variables of average wind speed, maximum wind speed, and average temperature. Pearson correlation coefficients (r) between different litterfall fractions and maximum wind speed are higher when compared to average wind speed. Moreover, the correlations were generally stronger with wind speed than with air temperature. Additionally, no significant correlation was observed for relative humidity or total precipitation. Among the correlations, there are five cases where r is greater than 0.4, signifying moderate to strong correlation. r-values between total litterfall and maximum wind speed is the highest, which is followed by that between needles litterfall and maximum wind speed. Furthermore, the correlation between the flower litterfall and temperature was also moderate to strong.

The scatter plots indicate that some occasions with high residual values for needles and total litterfall (Figure 5). These mostly appeared in 01/2022, 03/2021, and 11/2022 in descending order. Here, the high residual values all exceed 20gm^{-2}day^{-1}, once achieving 80 gm^{-2}day^{-1} for needles in 01/2022 and 110 gm^{-2}day^{-1} for all components combined in 01/2022 as well. As for twigs litterfall, most of its residual values fluctuate between ± 5gm^{-2}day^{-1}, with the rest three reaching 38gm^{-2}day^{-1} in 01/2022 specifically.

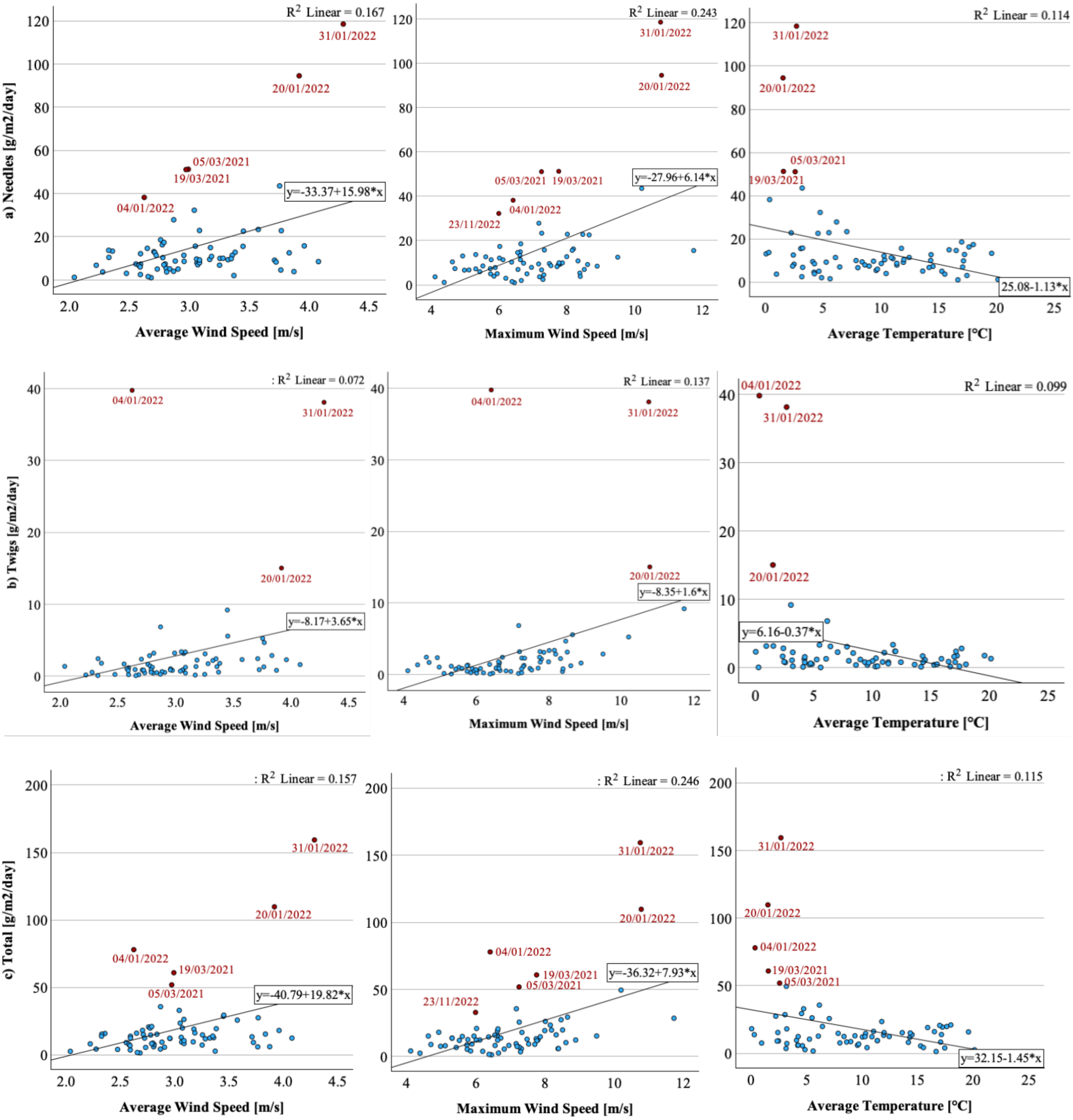

Figure 5: Correlation plots for litterfall fractions and climatic variables that are statistically significantly correlated: a) Needles litterfall, b) Twigs litterfall, and c) Total litterfall. Linearly fitted models for each plot are inserted. Their corresponding equations as well as R^2 are also attached. Red dots are residuals that exceeded 20gm^{-2}day^{-1}, occurring in 01/2022, 03/2021, and 11/2022.

Discussion

4.1 Total litterfall mass and proportions for each component

Average annual non-woody litterfall in this study area was 227.63gm^{2}yr^{-1}, which was equivalent to 2.3Mgha^{-1}yr^{-1}. This was slightly lower than the mean value of 3.3Mgha^{-1}yr^{-1} that reported for coniferous needle-leaved forests on a global scale (Zhang et al., 2014). Moreover, the rate was also lower than in mangrove forest (10.7 Mgha^{-1}yr^{-1}) and tropical evergreen forest (7Mgha^{-1}yr^{-1}) (Zhang et al., 2014). Such differences could be due to distinct species compositions, study areas, and sample sizes relative to the present study. Previous literatures have found that the forest litterfall is dependent on the complicated interactions between physiological mechanisms and environmental factors (Morffi-Mestre et al., 2020). During the succession course in forests, vegetation structure and species composition are changing accordingly, which have influences on litterfall (Celentano et al., 2011). It increases with the rising successional age as a result of the growth in leaf area index, size of trees, and aboveground biomass (Lebrija-Trejos et al., 2011). Litterfall is also related to topographical conditions since it influences solar radiation and soil water availability, which in turn affects phenology of trees (Gallardo-Cruz et al. 2019, Méndez-Alonzo et al. 2013). Apart from these, different climatic variables affect litterfall to various extent. This study only addressed wind speed, temperature, relative humidity, and precipitation. Other variables that might contribute to the complex interplay involve cloud cover (Wagner et al., 2016), incident solar radiation (Zalamea & González, 2008), and combined effects of several variables (Saarsalmi et al., 2007). Increasing cloud cover and decreasing solar radiation can reduce photosynthesis rate and growth rate, leading to shedding of premature foliage that are on the lower part of the trees.

The needles component owned the largest proportion of litterfall dry biomass, with a substantial contribution of 78%. Twigs took up 15% of the total litterfall and the remaining part went into fruits and flowers. This result coincides with what Zhang et al. (2014) has concluded in a literature review, which stated that needles and twigs litterfall account for 73% and 17%, respectively, for coniferous needle-leaved forests worldwide. Another research also supports this, suggesting that leaf senescence was the biggest contributor to litterfall (Portillo-Estrada et al., 2013). Yet it is worth mentioning that events with sudden high wind velocity or early frost could also stimulate falling of premature needles (Portillo-Estrada et al., 2013).

4.2 Litterfall mass and its relationship with climatic variables

Results support the original hypothesis, namely the litterfall is positively correlated to wind speed and the influence of wind speed outweighs that of temperature or relative humidity (Table 1 and Figure 5). It is noticeable that wind speed affects the amount of litterfall to varying degrees based on litterfall types, with needles, twigs, and total amount being the variables that correlated the most to maximum wind speed. However, fruits and flowers demonstrate nearly no significant correlation with either of the three climatic variables. This means that among wind speed, temperature, and relative humidity, maximum wind speed is the dominant climatic trigger for the falling of needles and twigs. Looking at the r values in Table 1, flowers litterfall amount is more related to temperature rather than other two climatic variables. Nevertheless, this does not imply that the flowers litterfall can be attributed to temperature variation. According to a research carried out by Skvareninova and Mrekaj (2022), flowering of Norway Spruce (*Picea Abies L.*) occurred between May and July in six decades. This indicates that it is the phenology of the flower itself rather than temperature which lead to the shedding. Instead of causally correlated, the correlations between them are rather spurious. The positive correlation between litterfall amount and wind speed aligns with prior findings (Kamruzzaman et al. (2013), Marod et al. (2023), Morffi-Mestre et al. (2020), Souza et al. (2019), Qiu et al. (2023)) although they were conducted in other parts of the world.

None of abovementioned articles have examined both average and maximum wind speed as independent variables. However, this study discovers that maximum wind speed is more related to litterfall amount compared with average wind speed. It could be inferred that dead needles and twigs remain on trees when not yet exposed to external factors; however, once a powerful stochastic event occurs (e.g., storm, heavy snowfall), their dropping mechanism is triggered. As a result, one could not claim that it is the wind that boosts the litterfall, it is rather a factor that causes the process of shedding withered materials. Aside from wind gusts, sustained wind with low speed has also been reported to cause similar effects on litterfall (Marod et al., 2023). For example, fruit litter response could be triggered by constant mechanical forcing of wind.

Even though this study finds that wind speed associates the most with litterfall mass among the three chosen variables, there are other literatures claiming conflicting results. As suggested by Kramer et al. (2000), the litterfall and seasonality in coniferous forests were mainly driven by temperature, because peaks appeared mostly in autumn and winter with lower temperature as relative to other seasons. Moreover, declining relative humidity combined with rising temperature reduce soil water content, inducing vapor pressure deficit and further boosting litterfall (Smith & Ennos, 2003). Nevertheless, the same article also mentioned that the falling of needles and branches could be amplified by high wind speed. In addition to wind speed, temperature, and relative humidity, incident solar radiation was also once documented by Zhang et al. (2014) as the dominant variable in coniferous needle-leaved forests, since litterfall mass peaked along with decreasing solar radiation.

4.3 Potential reasons behind the occurrence of residuals

Occasions with very high litterfall residual values occurred mostly in 01/2022, 03/2021, and 11/2022 (Figure 5). These might be explained by storm and heavy snow events (Figure 2). The storm Malik swept over southern Sweden from 29th to 30th January 2022. This extratropical cyclone was initially formed as a low-pressure zone above southern Greenland and Iceland on 27th and 28th, with partial low pressure shifting towards Scandinavia and hitting Sweden in the two following days (SMHI, 2022). During the event, the lowest reported air pressure was 962hPa, which broke the record in past two years (SMHI, 2022). Hurricane-induced gusts was reported to be 33.6 m/s at Falsterbo station in Skåne (SMHI, 2022). Although Hyltemossa is also inside Skåne, the highest wind speed only reached 10.8m/s on 31st (Figure 2). This can be attributed to its rather inland location and high density of trees. Another explanation is that the

33.6m/s was the maximum value whereas the 10.8m/s was the hourly average value. Despite its relatively low wind speed compared with along the coastline, substantial amount of litter was fallen from the forest stand due to the storm event, with values much larger than what derived from the linearly fitted model. Consequently, carbon storage inside the forest could have been affected by the rising number of residual debris (Lindroth et al., 2009).

Moving onto the other two months which contained prominent residuals, the recorded maximum wind speed was 7.8m/s in 03/2021 and 5.9m/s in 11/2022. These values were not far off from the mean maximum wind speed (i.e.: 7m/s) for the four-years period, indicating that storm wasn't the reason behind. Instead, abnormal litterfall mass might be attributed to heavy snow events. Public media have released news articles regarding two persistent heavy snowfalls, one started from 11th onwards in 03/2021 (TheLocal, 2021) and another from 19th onwards in 11/2022 (Thelocal, 2022). Skåne received a class-one snow warning in the former incident and a yellow snow warning in the latter one. According to SMHI (2024), the recorded snow depth during the two snowfalls was both in the range of 3cm to 10cm. Therefore, it could be the accumulated heavy snow acting as an external mechanical force which promoted the shedding of various litterfall components. A journal published by Wu et al. (2013) supports this, declaring that thick snow cover increased litterfall mass by nearly 6%, which further changed litter decomposition rate. Moreover, heavy snow could damage forest canopy, reducing the leaf area index, net ecosystem exchange, and ecosystem respiration (Song et al., 2017). The same article also proved that the annual net carbon uptake was diminished by 76% in the year with snowfall event as compared to the average annual value for previous years. As such, external disturbances such as storm and heavy snow are associated with litterfall increase. Nonetheless, comprehensive responses of litterfall to different disturbances is poorly evaluated, measurements should thus be recorded continuously over a long-term to comprehend the complicated process.

4.4 Uncertainties and future research suggestions

Although the hypothesis was confirmed by the results, several uncertainties and limitations were also involved. Firstly, the amount of data was inadequate to fully understand the seasonal pattern of litterfall mass inside the study area. The current data only covered four-years period, which was even less than the six-years lifespan of needles on *Picea Abies L.* (Norway spruce). Therefore, a more reasonable way to investigate the seasonal pattern would be to expand the measurements timespan. Additionally, there was a possible error in the data on 04/01/2022, which resulted in extremely high standard deviations (Figure 3a and 3b) and residuals in correlation plots (Figure 5). Apart from this, Hyltemossa is the only site included in this research, which can be improved by studying another coniferous forest site to make comparison. Furthermore, intercorrelations between the four chosen climatic variables might indirectly affect the derived correlation coefficients. For instance, the correlation coefficients between average temperature and average wind speed as well as maximum wind speed are both statistically significant at the two-tailed 0.01 level, with values of -0.452** and -0.382** (Appendix 1). Depending on the direction of the correlation between two independent variables, correlations between each independent variable and the dependent variable could be either strengthened or weakened. These negative correlations between temperature and wind speed indicates that the correlation between litterfall amount and wind speed or temperature might have been attenuated. Additionally, it is difficult to distinguish the litterfall that are fallen due to natural senescence from external disturbances. For example, a severe drought swept Sweden in 2018 and brought about negative influences on secondary managed forests, posing threat to carbon sequestration (Wolf et al., 2023). The drought-induced low soil water availability might have increased the synthesis of abscisic acid in the foliage (Edwards et al., 2018), leading to extra shedding in the beginning of 2019 as compared to under normal climatic condition. In terms of technical issues about the data collection, litterfall that initially dropped into the litter traps could have been blown out of the trap by wind gusts. This might end up with inaccurate litterfall value. Besides, the applied data was neither measured nor recorded by the author due to time constrains. Instead, it was derived from other researchers working for Lund University.

For future studies, one could focus on relationships between litterfall and other climatic variables, such as solar radiation, cloud cover, soil water content and so forth. As for the precipitation, rainfall intensity in mm/h could also be an alternative instead of the applied rainfall accumulation in mm. Regarding wind speed, the frequency of high wind speed could be a stronger variable to use. The overall response of litterfall mass to a specific event of external disturbances (storm, snow, drought) is also a suggested aspect. Another perspective to build upon this paper would be to quantify the influence of different climate variables on the litterfall. This could be achieved by using generalized linear models, random forest models or superposed epoch analysis (Marod et al., 2023). Of course, coarse woody debris is another candidate of litterfall component as well, yet data acquisition might be an issue due to the slow decomposition process of tree trucks and the long-time interval between measurements. No matter which of the abovementioned topics, continuous measurements over a long-term should be conducted to provide a basis for recognizing the underlying pattern.

Conclusion

Litterfall plays an essential role in the forest ecosystem, contributing to amongst other things terrestrial carbon storage (Dai et al., 2023), soil fertility maintenance (Spohn, 2023), and nutrient dynamics (Morffi-Mestre et al., 2020). It is crucial to quantify litterfall so that carbon dynamics, vegetation phenology, biogeochemical circulations could be evaluated and the recovery capacity of forests from disturbances could be monitored (Morffi-Mestre et al., 2020). Identifying dominant climatic factors that trigger litterfall provides us a deeper understanding of how the forest ecosystem responses to the undergoing climate change.

This study aimed to investigate the relationship between non-woody litterfall and climate variables, including wind speed, air temperature, relative humidity, and precipitation, in a coniferous forest at Hyltemossa research site. This was fulfilled by first understanding the meteorological conditions in the study area, then analyzing the phenology of different litterfall components (needles, twigs, fruits, flowers, and total), and finally conducting correlation analysis between variables. The results found that the litterfall of needles, twigs, and total were positively correlated to average wind speed and maximum wind speed, whereas negatively correlated to average temperature. Besides, the correlations of litterfall with wind speed were stronger than with other climate variables. Therefore, the hypothesis that wind speed rather than air temperature, relative humidity, and precipitation is expected to have a stronger influence on litterfall was not rejected. Flowers litterfall and temperature was also positively correlated, yet this was more likely due to the phenology of the flower itself, which tend to drop off during summer. In terms of the phenology, most needles and twigs fell during late winter or early spring, contributing 78% and 15% to the total non-woody litterfall, respectively. Flowers tended to fall in summer and late spring, whereas fruits occurred mostly in late winter and only took up a tiny proportion of the total litterfall. Additionally, external disturbances such as storm and heavy snow are associated with litterfall increase. Future studies could investigate the impact of different climate variables on the litterfall, either by quantifying the influence of each variable or by exploring other variables such as cloud cover and solar radiation. One could also include the coarse woody fraction when examining different litterfall components.

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Appendix 1

		Needles	Twigs	Fruits	Flowers	Total	WS_Ave	WS_Max	Ta_Ave	Ta_Max	RH_Ave	P_Total
Needles	Pearson Correlation	1	.982**	.953**	.956**	1.000**	.050	.060	-.055	-.050	-.007	-.186
	Sig. (2-tailed)		<.001	<.001	<.001	<.001	.672	.617	.643	.675	.954	.120
	N	73	73	73	73	72	73	73	73	73	73	71
Twigs	Pearson Correlation	.982**	1	.933**	.931**	.987**	.060	.082	-.087	-.077	.005	.037
	Sig. (2-tailed)	<.001		<.001	<.001	<.001	.616	.490	.466	.515	.967	.758
	N	73	73	73	73	72	73	73	73	73	73	71
Fruits	Pearson Correlation	.953**	.933**	1	.922**	.956**	.012	.044	-.035	-.016	-.065	-.049
	Sig. (2-tailed)	<.001	<.001		<.001	<.001	.921	.710	.767	.894	.584	.686
	N	73	73	73	73	72	73	73	73	73	73	71
Flowers	Pearson Correlation	.956**	.931**	.922**	1	.957**	-.019	-.032	.094	.096	-.070	-.127
	Sig. (2-tailed)	<.001	<.001	<.001		<.001	.870	.791	.430	.417	.555	.292
	N	73	73	73	73	72	73	73	73	73	73	71
Total	Pearson Correlation	1.000**	.987**	.956**	.957**	1	.059	.074	-.051	-.044	-.004	-.144
	Sig. (2-tailed)	<.001	<.001	<.001	<.001		.622	.535	.673	.712	.971	.230
	N	72	72	72	72	72	72	72	72	72	72	71
WS_Ave	Pearson Correlation	.050	.060	.012	-.019	.059	1	.786**	-.297*	-.305**	.170	.133
	Sig. (2-tailed)	.672	.616	.921	.870	.622		<.001	.010	.008	.148	.267
	N	73	73	73	73	72	74	74	74	74	74	71
WS_Max	Pearson Correlation	.060	.082	.044	-.032	.074	.786**	1	-.221	-.238*	.170	.165
	Sig. (2-tailed)	.617	.490	.710	.791	.535	<.001		.059	.041	.148	.168
	N	73	73	73	73	72	74	74	74	74	74	71
Ta_Ave	Pearson Correlation	-.055	-.087	-.035	.094	-.051	-.297*	-.221	1	.947**	-.192	.049
	Sig. (2-tailed)	.643	.466	.767	.430	.673	.010	.059		<.001	.101	.687
	N	73	73	73	73	72	74	74	74	74	74	71
Ta_Max	Pearson Correlation	-.050	-.077	-.016	.096	-.044	-.305**	-.238*	.947**	1	-.324**	-.023
	Sig. (2-tailed)	.675	.515	.894	.417	.712	.008	.041	<.001		.005	.850
	N	73	73	73	73	72	74	74	74	74	74	71
RH_Ave	Pearson Correlation	-.007	.005	-.065	-.070	-.004	.170	.170	-.192	-.324**	1	.381**
	Sig. (2-tailed)	.954	.967	.584	.555	.971	.148	.148	.101	.005		.001
	N	73	73	73	73	72	74	74	74	74	74	71
P_Total	Pearson Correlation	-.186	.037	-.049	-.127	-.144	.133	.165	.049	-.023	.381**	1
	Sig. (2-tailed)	.120	.758	.686	.292	.230	.267	.168	.687	.850	.001	
	N	71	71	71	71	71	71	71	71	71	71	71

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).