FutureWater

MIT-haalbaarheidsproject

Haalbaarheidsonderzoek: voorkomen van vorstschade in fruitteelt door flying sensors

RAPPORT 231

OPDRACHTGEVER Provincie Gelderland

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Omslagfoto: Windturbine voor vorstbescherming in de fruitteelt bij Vogelaar Vredehof in Krabbendijke, Zeeland, waar als onderdeel van dit haalbaarheidsproject verschillende drone vluchten zijn uitgevoerd.

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Project details

De Mkb-innovatiestimulering Regio en Topsectoren (MIT) regeling is in 2015 van start gegaan en heeft als doelstelling:

Innovatie bij het midden- en kleinbedrijf over regiogrenzen heen te stimuleren.

In samenwerking met HiView heeft FutureWater in 2020 bij de Provincie Gelderland een voorstel ingediend voor deze MIT-regeling voor het instrument haalbaarheid met de titel:

Voorkomen van vorstschade in fruitteelt door flying sensors

Op 30 Juni 2020 heeft de Provincie Gelderland besloten subsidie te verlenen aan FutureWater voor dit project. Administratieve details zijn:

- Projectnaam: Voorkomen van vorstschade in fruitteelt door flying sensors
- Naam subsidieontvanger: FutureWater B.V.
- Topsector: Agri en Food
- Looptijd: 7 april 2020 t/m 30 september 2021
- Referentienummer: 2020-005039

Dit rapport geeft een overzicht van de resultaten van het uitgevoerde haalbaarheidsproject.

FutureWater waardeert de financiële ondersteuning die ontvangen is van de Provincie Gelderland voor het uitvoeren van dit haalbaarheidsproject.

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1 Introduction

Fruitteelt is een belangrijke economische motor voor Nederland. Met een totale jaarlijkse omzet van ongeveer 500 miljoen euro is Nederland groot in de productie, import en export van hard- en zachtfruit. In totaal zijn er in Nederland ruim 1300 fruitbedrijven met ieder een gemiddelde standaardopbrengst van ruim 320.000 euro.

Wanneer in het voorjaar de temperatuur in de nachten daalt tot onder het vriespunt en fruitbomen in de knop staan moeten fruittelers hun gewassen gaan beschermen. Als de knoppen kapot zouden vriezen dan kan er over een aantal maanden niet worden geoogst waardoor een enorme economische schadepost ontstaat. Het klinkt tegenstrijdig, maar als gevolg van klimaatverandering neemt het risico op deze vorstschade in de fruitteelt in Nederland alsmaar toe. Door de stijgende temperaturen krijgen we namelijk steeds vroegere voorjaren en komen fruitbomen als gevolg gemiddeld bijna twee weken eerder in bloei dan in de jaren ‘80. Hierdoor worden fruitbomen dus gemiddeld vaker aan nachtvorst blootgesteld. Ook tijdens zachte winters is de kans op nachtvorst groot. Anders gezegd, het risico op vorstschade in de fruitsector neemt de komende jaren alleen maar toe.

Het beschermen van de knoppen gebeurt meestal met behulp van water. Deze vorm van vorstbescherming vergt veel water - er is gemiddeld 30 m3 per hectare per uur nodig - en als er meerdere nachten aaneen nachtvorst optreedt, kan de limiet aan waterbeschikbaarheid snel worden bereikt. Bovendien lopen de kosten voor fruittelers dan enorm op. Ook kan het water, als de kwaliteit hiervan niet toereikend is (bv. door brakheid), schade aanbrengen aan de gewassen. Hierdoor kan ongeveer 30% van de fruitbedrijven in Nederland geen gebruik maken van water voor nachtvorstbescherming.

Met het oog hierop is de inzet van windmachines om fruitbomen te beschermen tegen nachtvorst, als alternatief voor water, een veelbelovende nieuwe en innovatieve techniek die in het buitenland al veelvuldig wordt ingezet. De propeller van de windmachine vermengt de koude lucht met de hogere warmere lucht en kan zo de temperatuur aan de grond met enkele graden verhogen. Andersom kan het systeem in de zomer de temperatuur met behulp van luchtcirculatie juist omlaag brengen en zo zonnebrand op de bomen voorkomen. Ervaring uit het buitenland leert dat windmachines gemakkelijk 25 jaar meegaan zonder al te grote onderhoudskosten en dat de kostprijs per hectare per jaar ongeveer 300 euro bedraagt. Hierdoor zijn windmachines dus een zeer kosteneffectief alternatief voor het sproeien van water voor vorstbescherming. Bovendien wordt Nederland steeds droger (niet alleen in de zomer maar ook gedurende de lentemaanden neemt regenval af), waardoor waterbesparende en klimaatbestendige maatregelen steeds vaker nodig zijn om de waterhuishouding op peil te houden.

De inzet van windmachines voor vorstbescherming in de fruitteelt is echter maatwerk, waarbij de toepassing nauwgezet moet worden afgestemd met de individuele fruitteler. De ervaring leert dat hierbij niet alleen gekeken moet worden naar capaciteit van de windmachine, maar dat ook de eigenschappen van het perceel en omliggende landschapselementen van grote invloed zijn op de doeltreffendheid van windmachines. In dit proces bieden drones (vanaf nu *flying sensors* genoemd) een grote meerwaarde; tegen lage kosten en met een hoge operationele flexibiliteit kunnen fruitpercelen en omliggende percelen snel en precies in kaart worden gebracht. Dit gebeurt normaal gesproken met een normale camera, maar binnen dit haalbaarheidsproject wordt de toepassing en geschiktheid van een thermische warmtebeeldcamera onderzocht. Omdat dit type camera de temperatuur van objecten en omgeving kan meten, kan de werking van windmachines ruimtelijk in beeld worden gebracht. Door over een fruitperceel te vliegen wanneer de windmachines aan staan, kan in real-time worden gemeten met hoeveel graden de temperatuur wordt verhoogd en hoe het ruimtelijke patroon van die temperatuurverhoging eruitziet.

Binnen deze context onderzoekt dit haalbaarheidsproject '*de kansen van een innovatieproject voor het monitoren van de effectiviteit van windmachines als vorst beschermende maatregel in de fruitteelt met behulp van flying sensors (drones) uitgerust met een thermische warmtebeeldcamera.'*

De resultaten van dit haalbaarheidsproject zullen via een ontwikkelingsproject kunnen leiden tot een innovatieve informatiedienst aan fruittelers om (1) inzicht te bieden in de effectiviteit van windmachines voor vorstbescherming en (2) te adviseren hoe de toepassing van windmachines kan worden geoptimaliseerd voor hun perceel en/of gewas. In het voorziene ontwikkelingstraject zal een prototype van deze dienst worden ontwikkeld en gedemonstreerd voor een pilot-gebied. Aangezien deze toepassing zeer innovatief is, is dit een risicovolle aanpak met een reële kans dat het niet het gewenste resultaat oplevert. Subsidie voor deze haalbaarheidsstudie is dus noodzakelijk en gericht op de volgende onderdelen:

Projectonderdelen zoals weergegeven in het voorstel

1. Economische haalbaarheid
   1.1. Haalbaarheidsanalyse: Geografische analyse en kansenkaart waar de inzet van windmachines kansen biedt voor een duurzamere fruitteelt: (1) Ruimtelijke analyse op basis van sociaaleconomische data over fruitteelt in Nederland, met behulp van GIS-software en bestaande databases; (2) Ruimtelijke analyse op basis van fysisch geografische data uit public-domain databases over waterbeschikbaarheid en waterkwaliteit.
   1.2. Marktverkenning en concurrentieanalyse: Een verdere detaillering van de totale markt zal worden gemaakt, met de focus op gebieden die in activiteit 1.1 kansrijk blijken. Naast het in kaart brengen van eindgebruikers is een belangrijke activiteit om een gedetailleerd overzicht te maken van bestaande informatiediensten.
   1.3. Kosten-baten analyse: Op basis van de marktpotentieel analyse, gecombineerd met een eerste orde kosten- en batenanalyse kan worden bepaald wat de kosten-baten zijn. Aan de kostenkant zal worden gekeken naar de kosten van het informatiesysteem m.b.v. flying sensors en de windmachines zelf, t.o.v. bestaande technieken en aan de batenkant zal worden gekeken naar de potentiële verhoging van de oogsten, door afnemen van vorstschade. Dit zal worden uitgevoerd voor zowel de eindgebruikers (dus als onderdeel van de marketing) als voor FutureWater en partners zelf.
2. Technische haalbaarheid
   2.1. Literatuuronderzoek: De laatste ontwikkelingen en inzichten m.b.t. inzet van windmachines voor vorstbescherming in de fruitteelt worden onderzocht, gebaseerd op wetenschappelijk onderzoek maar ook op het raadplegen van rapporten en productomschrijvingen van bedrijven die actief zijn in de sector.
   2.2. Inventarisatie benodigdheden informatiedienst voor fruittelers: Inventarisatie van benodigde technieken om thermische warmtebeelden te interpreteren en ruimtelijke drone data te visualiseren voor eindgebruikers. Tevens worden opties onderzocht op welke manier deze tools kunnen worden geïntegreerd in een webapplicatie, voor een toegankelijke en gebruiksvriendelijke ervaring voor eindgebruikers van de voorziene informatiedienst.

1.1 Background on frost damage in fruit crops

Frost is one of the most harmful weather events, causing recurrent and significant damage in agriculture (Beyá-Marshall et al., 2019). Crops frost damage is generated when the air temperature drops below 0°C, freezing the crops in which the extracellular water within the plant changes from liquid to ice. Moreover, freeze injury occurs when the plant tissue temperature falls below a critical value called 'critical temperature' (T_c) that is an irreversible physiological condition conducive to death or malfunction of the plant cells (FAO, 2005).

There are two types of frost events: radiation frost and advection frost. The radiation frost occurs at night due to intense, longwave radiation cooling under clear skies and calm or light wind conditions (less than

1.8 m s−1) (Beyá-Marshall et al., 2019). It is characterized by a temperature inversion, low dew-point temperatures, and air temperatures that typically fall below 0°C during the night but are above 0°C during the day (FAO, 2005). In contrast, the advection frost occurs when cold air blows into an area to replace warmer air before the weather changes. It is associated with cloudy conditions, moderate to strong winds, no temperature inversion, and low humidity. Often temperatures drop below the melting point (0 °C) and stay there all day (FAO, 2005).

Furthermore, the frost damage level depends on climatic (minimum temperature and frost duration) and agronomic factors (species, degree of acclimatization, phenological state, plant tissue, variety, rootstock, vigor, and level of fruit crop) (Beyá-Marshall et al., 2019). For example, one of the agricultural sectors most affected by night frost is fruit production. In this case, large fruits, bud, flower, and small-fruit temperature tends to be colder than the air temperature. Therefore, a drop in temperature at night becomes destructive fruit crops, ranging from -3 to -4°C, severely impacting the crop's production (Kotikot & Onywere, 2015).

Moreover, frost generates losses in production, both volume and quality. It also impacts the social and economic security of the regions involved, affecting farmers, agricultural workers, and rural families (Beyá-Marshall et al., 2019). Therefore, several protection methods can be applied to prevent the crops frost damage. These methods are classified into two groups: passive and active protection. On the one hand, passive (indirect) protection includes implemented methods before a frost night like crop site selection, cold air drainage with trees, bushes, mounds of soil, and plant nutrition management.

On the other hand, active (direct) protection methods are carried out during the frost night to mitigate temperatures below 0°C. Some examples of active protections methods are heaters, helicopters, sprinklers, and wind machines (FAO, 2005). Although over vine sprinkling systems offer the "highest level of protection of any available system", they are frequently not practical because of the substantial water resources needed for this type of protection (Poling, 2008). Moreover, for radiative frost events in Large fruit crops (e.g., oranges), bud, flower, and small-fruit temperatures tend to be colder than the air temperature. So active protection methods should be started and stopped at higher air temperatures than the critical' ones (FAO, 2005).

1.1.1 Impact of frost damage to Dutch fruit growth industry

Frost damage has always been one of the main concerns of the fruit growers in the Netherlands, and it is an issue that has been getting more critical due to global warming. This phenomenon overtime is increasing caused by temperature rise due to climate change. The temperature rise generates that plants bud/germinate earlier, as well as fruit trees blossom earlier. Consequently, the earlier germination and blossoming are the greater risk of night fruit frost damage in early spring. This risk is exceptionally high for Dutch fruit growers (Bresser et al., 2006).

Figure 1 shows the critical temperature that several fruit crops can tolerate concerning different development stages. Stage 1 refers to the onset of bud activity; stage 2 is the bud burst; stage 3 is the bloom or first leaf for grapes; stage 4 indicates the post-bloom or fourth leaf for grapes. Moreover, the T_{10} and T_{90} are the temperatures where 10% and 90% of the commercial crop production is likely to be damaged (Miranda et al., 2019).

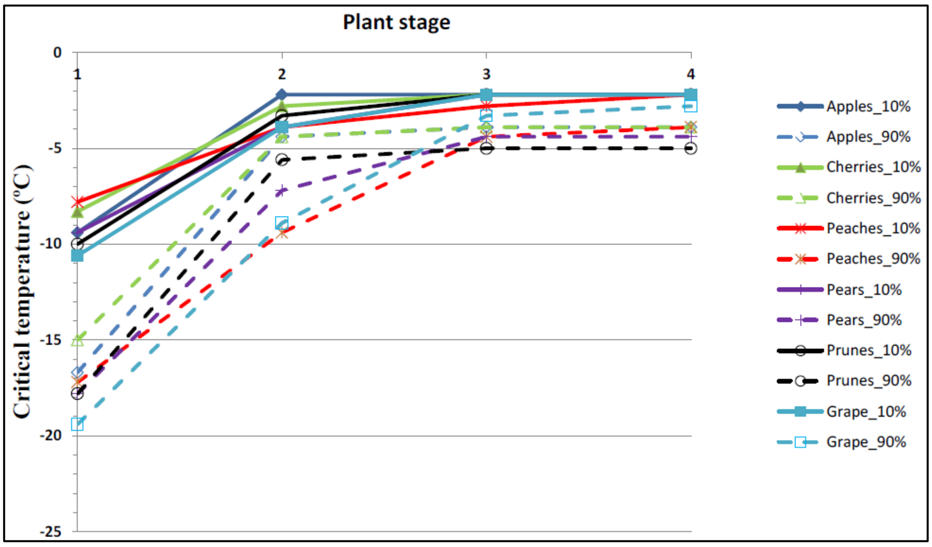


Figure 1 Critical damage temperature in relation to the developmental stage of some fruit trees and grapes (Miranda et al., 2019)

According to Figure 1, the fruit trees start losing 10% of their production during the bud burst stage with a temperature below -2°C. Besides, as the stage of the crop progresses (blooming and post-blooming), they become more sensitive to a drop in temperature. Most of them start being highly sensitive to a temperature below 0°C fluctuations, presenting 10 % of yield lost at a temperature below -2°C, and 90% of crop lost at temperatures between -3 to -5°C. Therefore, as crop development is brought forward due to climate change, yield is more exposed to frost damage in the early spring in the Netherlands.

Spring freezes are almost a certainty in any given year in the Netherlands. For that reason, fruit growers need to constantly assess the stage of development of their crops and the susceptibility to freeze injury (Longstroth & Irish-Brown, 2021). In 2005 a severe frost fruit damage in the province of Flevoland occurred. As a result, apple and pear trees reduced the volume of their blossoms to half. Compared to the bumper crop year 2004, apple and pear crops were reduced by 18 and 75% respectively. Besides, the area covered by pear orchards rose by 3% to 6.7 thousand ha, and the apple orchard area covered 9.7 thousand ha, presented a 5% reduction compared to 2004 (CBS, 2006).

More recently, during spring 2021, the lowest temperatures were recorded in the center and south of the Netherlands, with temperatures between -2 and -2.5°C in many places, alerting the fruit growers. Therefore, the fruit was exposed to 10% loss or reach a 75% loss of the yield without a frost protection method (AGF, 2021). As a result, the fruit was exposed to 10% loss or reached a 75% yield loss without a frost protection method. Hence, it is strictly necessary to use a frost protection method to prevent and reduce fruit crop yield loss.

In the Netherlands, over vine sprinkling is commonly used as an active method to address radiative frost fruit damage. Due to its operational costs are low as well as its labor requirement. However, the main disadvantage of applying this method is the large amounts of freshwater needed (FAO, 2005). Although the local water authorities handle water management, regulation, and allocation well, the water quality and availability problems are the main reasons farmers have been looking for different sustainable frost protection methods.

Wind machines have been used as a sustainable frost protection method for approximately 30 years in the Netherlands. This method is one of the cheapest anti-frost solutions per hectare. In addition, the machine's lifespan is more than 30 years, and the annual maintenance/operation only amounts to one person/hour per year (De Ridder, 2020). Furthermore, the machine rotates on its axis, and it protects a circular surface of about 7 hectares at a temperature of -3°C. Thus, preventing 10 to 90% of fruit yield loss during the bud burst and blooming stage (Figure 1).

In most of the Dutch provinces, wind machines perform satisfactorily. However, for the machine to work optimally, it must run parallel to the slope of the terrain. For instance, this is not a problem in provinces like Zeeland, but in Limburg and other regions with a steep slope, they often have to be placed at a slight angle (De Ridder, 2020). Therefore, wind machines are a feasible frost protection method that adapts well to the Dutch fruit growers' geographic and socio-economic conditions.

1.1.2 FutureWater's track record on flying sensors

FutureWater has worked in several projects in which flying sensors have been used to predict, monitor, and assess agricultural projects.

Table 1 Projects undertaken by FutureWater related to flying sensors

Title	Year	Client	Country
HiFarm Kenya: Flying Sensors to Improve Productivity of Maize, Coffee, and Tea Farmers	2021-2021	Eco business fund	Kenya
A Practical Farmers' Toolkit – Geodata for Climate Smart Agriculture	2021	RVO	Egypt
Apsan-Vale: Piloting Innovations to Increase Water Productivity and Food Security in Mozambique	2018-2021	Agência do Zambeze	Mozambique
SMART-WADI: SMART WAter Decisions for Iran	2018-2019	RVO	Iran
TWIGA: Transforming Weather Water data into value-added Information services for sustainable Growth in Africa	2018-2022	European Commission	Ghana, Mozambique
ThirdEye: Flying Sensors to Support Farmers' Decision Making	2014-2019	USAID, SNV	Kenya

2 Economic feasibility

2.1 Socio-economic analysis and opportunities map

This section covers socio-economic factors to find out where wind machines have the most significant potential. In addition, this analysis considers the availability and quality of the water accessible for irrigating water on fruit crops as a method of frost protection. Therefore, the wind machines potential users in the Netherlands are in areas where the fruit producers cannot easily access water or do not have a good water quality for sprinkling against the frost.

2.1.1 Fruit growers distributed through the waterboards

The Netherlands is a great fruit producer with a total annual turnover of approximately 500 million euros, with over 1300 fruit companies distributed across the country. Figure 2 shows the fruit growers distribution concerning the waterboards of the Netherlands. In which, most of these producers are in the southern half of the country.

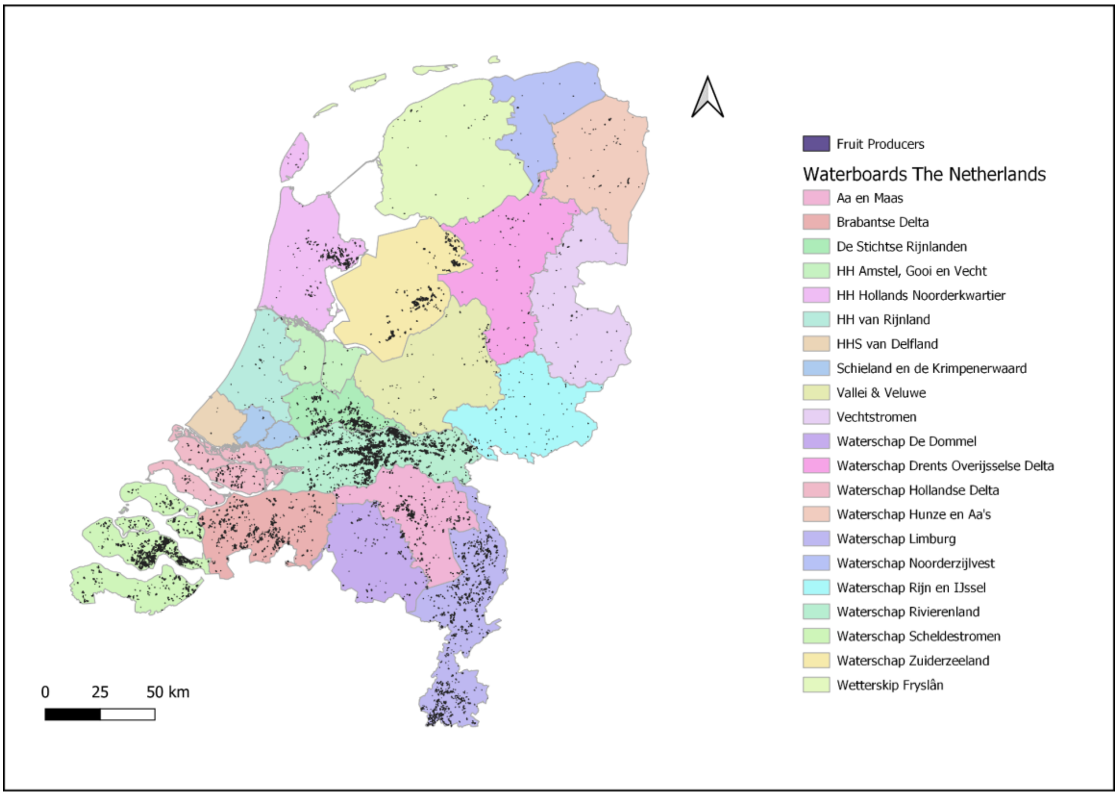
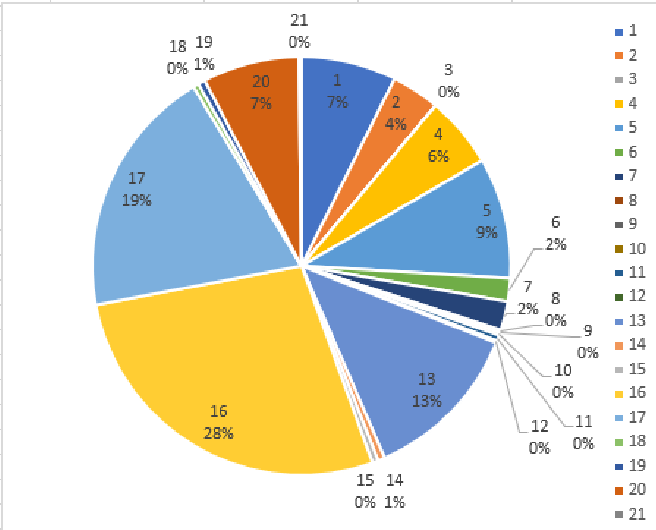


Figure 2 Distribution of the fruit producers through the waterboards in the Netherlands

The waterboards' regulations govern fruit growers regarding groundwater and service water usage for irrigation and frost protection purposes. Figure 3 shows the area cover percentage of fruit producers along each waterboard. For instance, the Rivierenland waterboard has 28% of the area covered over the total area covered around the country by fruit producers, followed by the Scheldestromen waterboard with 19% and Limburg waterboard with 13%. These three waterboards are the ones that hold most of the fruit producers in the country. Which includes the following provinces: Limburg, Gelderland, North-Brabant, Utrecht, South-Holland, and Zeeland.



1	De Stichtse Rijnlanden
2	HH Hollands Noorderkwartier
3	HHS van Delfland
4	Aa en Maas
5	Brabantse Delta
6	Waterschap De Dommel
7	Waterschap Hollandse Delta
8	HH van Rijnland
9	Schieland en de Krimpenerwaard
10	HH Amstel, Gooi en Vecht
11	Waterschap Hunze en Aa's
12	Waterschap Noorderzijlvest
13	Waterschap Limburg
14	Waterschap Drents Overijsselse Delta
15	Waterschap Rijn en IJssel
16	Waterschap Rivierenland
17	Waterschap Scheldestromen
18	Vechtstromen
19	Vallei & Veluwe
20	Waterschap Zuiderzeeland
21	Wetterskip Fryslân

Figure 3 Percentage of area cover by fruit producers at Waterboards

Moreover, during periods of water shortage, the distribution of the available water in the national waters is determined according to the National Priority List. The distribution of regional waters is subject to regional priority lists based on the national list, in which agriculture is low on the list of priorities (Deltafacts, 2021). As farming is a low priority, the water that reaches the fruit crops during these scarcity periods is designated to fulfill the crop's water requirement and not for complementary functions as a frost protection method.

2.1.2 Fruit producer's distribution through the groundwater quality in the Netherlands

Groundwater is commonly used to sprinkle crop water and frost protection demand in farming areas where the service water is restricted. Moreover, the quality of this water should fulfill some standards to use it for agricultural purposes. However, in many regions, the groundwater quality is affected by salinity problems, mainly in the coastal areas. Figure 4 shows the relation between the salinity concentration in water and the damage percentage at the entire growing season of several crops. Fruit crops are affected from 700 mg Cl/l upwards. At 1000 mg Cl/l, the fruit tree damage reaches 15% due to salty groundwater, a high percentage of crop yield loss.

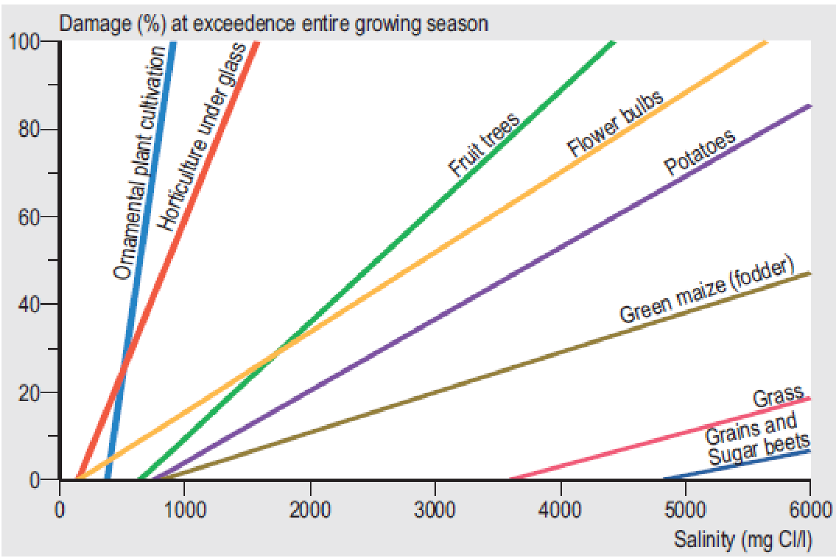


Figure 4 Relation between salinity and damage in crops (Bresser et al., 2006)

Furthermore, many regions in the Netherlands, mainly the coastal areas, are affected by saline groundwater seepage. At around 4 meters or below, the groundwater exhibits a degree of salinity, either brackish or saline (Iain Gould et al., 2021). Figure 5 describes the behavior of salty groundwater (1000 mg/l CL) below the ground level. The provinces that have more issues are Zeeland and Friesland. Here, groundwater lies close to the surface, and productive agricultural systems may increasingly rely on freshwater from surface water for production (Iain Gould et al., 2021).

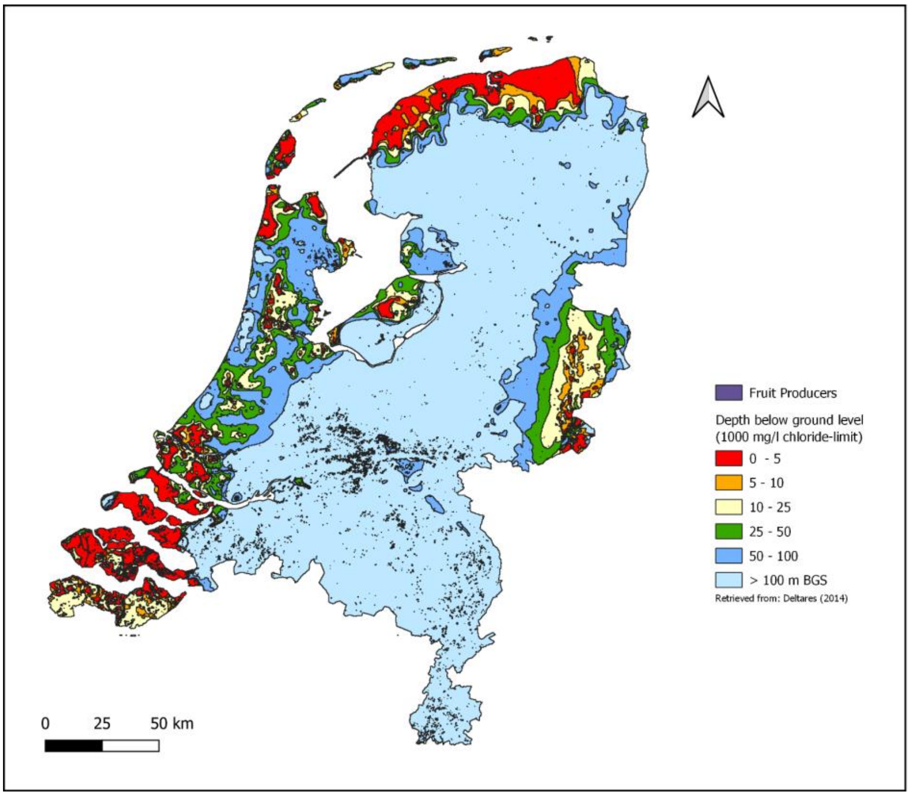


Figure 5 Groundwater salinity behavior vs. distribution fruit producers in the Netherlands

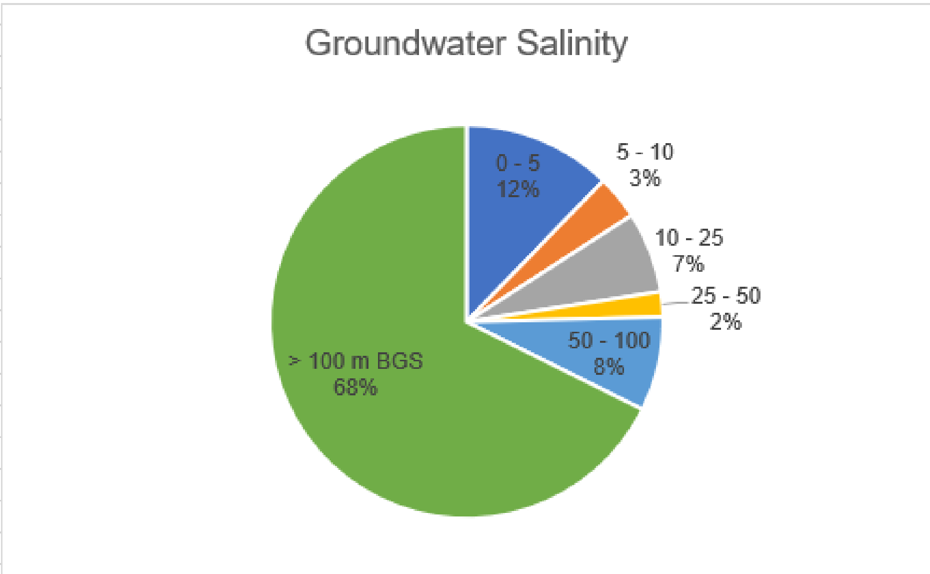


Figure 6 Percentage of Dutch fruit growers about the salty groundwater levels

Figure 6 shows the percentage of fruit growers regarding the groundwater salinity depth below ground level in the Netherlands. In general terms, due to groundwater salinity, 68% of the fruit growers don't have any water quality issues. However, 12% of the country's fruit crops endanger salty groundwater between 0 to 5 m below the ground level. Most of these fruit growers are located in the region of Zeeland that, as mentioned before, is a coastal region, salty levels rise as a result of groundwater seepage from the sea (Iain Gould et al., 2021).

In conclusion, in the coastal areas of the Netherlands, freshwater cannot always be ensured by the waterboards for agricultural purposes. And fruit crops cannot be irrigated with lousy water quality because their production can be negatively affected. Therefore, the waterboards should at least ensure the crop water requirement. And for frost protection purposes, fruit growers should search for different alternatives, apart from sprinkling, to provide crop protection efficiently, as wind machines.

2.2 Geographic Analysis on wind machines potential

This section covers socio-economic factors to determine the fruit producers potentially wind machine users to overcome the bud frosting during spring.

2.2.1 Water availability in the main waterboards concerning fruit production

Water usage in agriculture is also highly dependent on weather conditions. Due to the precipitation deficit in the Netherlands, fields and grasslands were irrigated more significantly in 2018 than in previous years. The agricultural sector used 302 million cubic meters of water, over 150% more than 2017 and over 50% more than in 2003, a similarly dry year. Arable farmers used almost four times as much surface water and groundwater as the previous year (CBS, 2020).

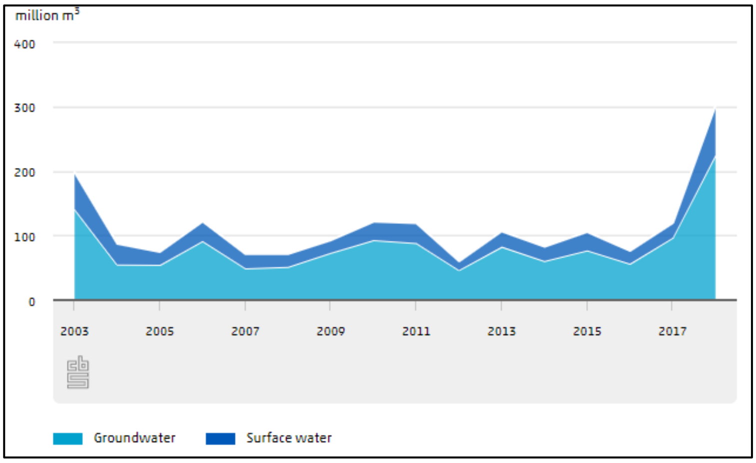


Figure 7 Abstraction of groundwater and surface water in agriculture (CBS, 2020)

After 2018 the water usage in agriculture increased, as is shown in Figure 7. This consumption involves surface and groundwater as being the two available freshwater resources for irrigation purposes. The waterboards regulate the water resources usage, control, and distribution. For this reason, fruit growers have to contact their corresponding waterboard to use water to fulfill the crop water requirement and sprinkle against frost damage.

Moreover, each waterboard has its regulation depending mainly on the water resources availability. The following are some of the actions that producers must take into account when using water for irrigation and sprinkling, in this case for frost prevention, depending on the corresponding waterboard:

Rivierenland waterboard

The Revierenland waterboard integrates the provinces of South Holland, Gelderland, North Brabant, and Utrecht. On the one hand, the fruit growers located in the Rivierenland waterboard must ask for a permit for works and activities in, on, and near waterways, following the general rules that the waterboard has drawn up. On the other hand, the groundwater abstraction for sprinkling and irrigating is exempt from a permit requirement. This activity is considered with a low chance of irreparable damage to the environment.

Scheldestromen waterboard

The Scheldestromen waterboard rules the water management of the province of Zeeland. This waterboard regulates most of the dikes and dunes in Zeeland (almost 500 km) because it is a province under sea level. Therefore, most of its efforts are to ensure water quality preventing salinity intrusions, paying attention to the ecology and chemistry of the water. In ecology, we look at plants and animals, such as fish that belong to that water type. In chemistry, they look at the sight of substances in the water, mainly oxygen and salt content (Scheldestromen, 2021).

Limburg waterboard

The Limburg waterboard regulates the entire province of Limburg that is characterized for having considerable groundwater and surface water reserves. Figure 8 shows Limburg's surface water distribution, highlighting the fruit growers' distribution in this province. Moreover, the extraction of groundwater or surface water is pumping this water to use for particular purposes, like farming. Hence, fruit producers in Limburg must issue a digital permit to ensure compliance with the regulations for preventing drought and damage to the environment (WL, 2021).

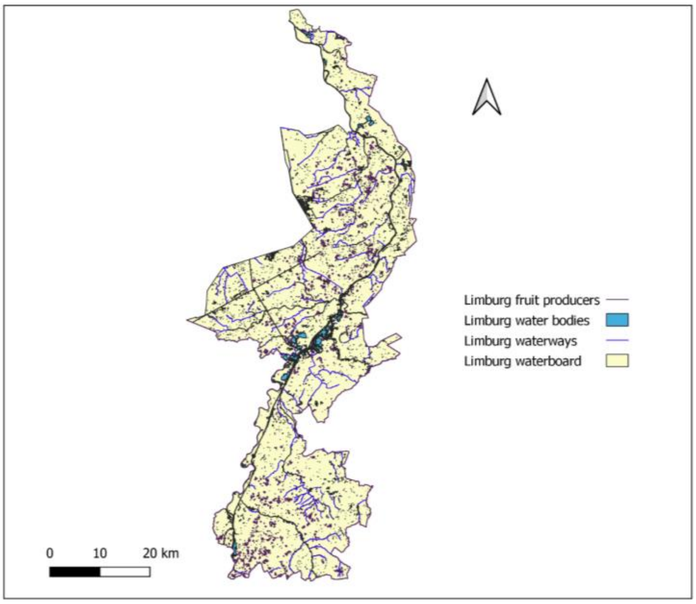


Figure 8. Limburg waterboard

Furthermore, Figure 9 shows the groundwater withdrawals for sprinkling open crops in the jurisdiction of the Limburg waterboard. There was a withdrawals' pick during 2018 due to the precipitation deficit that occurred in the country (see Figure 7). From that year, the water consumption for irrigating open crops purposes has been increasing. Therefore, each year is becoming more difficult for fruit producers to access freshwater for sprinkling water during a frost event. The Limburg waterboard would restrict its use to prevent any environmental damage.

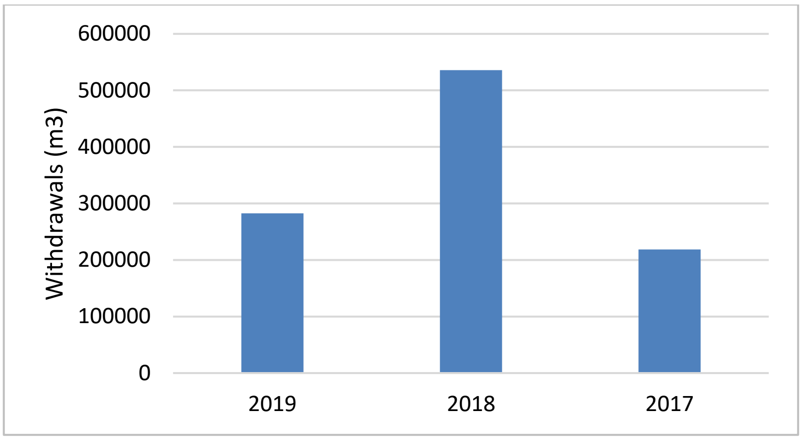


Figure 9 Groundwater withdrawals for sprinkling and irrigating open crops in Limburg waterboard

2.3 Cost-Benefit analysis of wind machines

The Cost-Benefit Analysis of wind machines as a good alternative for fruit frost prevention is mainly based on the information provided by the Energy Knowledge Center (KCE), a multidisciplinary center focused on the management of energy systems in buildings and greenhouse horticulture. Therefore, this economic analysis summarizes the essential information related to the development of this report extracted from its FROSTInno tool[1].

2.3.1 Comparison of wind machines with other active frost protection methods

In the market, several methods are offered for fruit frost protection. Their selection depends on the crop, cost, area, natural resources availability, and the method's efficiency. Therefore, several facts must be taken into account when selecting a fruit frost protection method. based on the yield and income obtained per hectare in three fruit frost cases (heavy, light, and limited frost year).

Table 2 presents a comparison of the most common frost protection methods in an apple and pear crop based on the yield and income obtained per hectare in three fruit frost cases (heavy, light, and limited frost year).

Table 2 Crop performance comparison with several active frost protection methods (KCE & Proefcentrum Fruitteelt VZW, 2021), * Average yield with no frost and no other significant setbacks

Type of fruit crop	*Average yield (ton/ha)	Average price (€/kg)	Type of active frost protection	Heavy frost year		Light frost year		Limited frost year	
				Yield (ton/ha)	Income (€/ha)	Yield (ton/ha)	Income (€/ha)	Yield (ton/ha)	Income (€/ha)
Jonagold apple average frost-sensitive plot	60	0,5625	No active frost protection	20	11250	30	16875	55	30937,5
			Warm air (Frostguard)	30	16875	50	28125	60	33750
			Warm air (Frostbuster)	40	22500	50	28125	60	33750
			Top crown irrigation	60	33750	60	33750	60	33750
			Wind machine	40	22500	50	28125	60	33750
Conference pear average frost-sensitive plot	50	0,5375	No active frost protection	45	24188	47	252623	48	25800
			Warm air (Frostguard)	48	25800	48	25800	50	26875
			Warm air (Frostbuster)	48	25800	49	26338	50	26875
			Top crown irrigation	50	26875	50	26875	50	26875
			Wind machine	48	25800	49	26338	50	26875

[1] https://www.pcfruit.be/nl/fruitteler/bedrijfsbegeleiding/vorstbescherming/economische-haalbaarheid

In general, all the frost protection methods increase the yield and the income compared to the crops without an active frost protection method, which shows the need to include a form of fruit frost protection. Furthermore, regarding the crop performance demonstrated by the methods, the heaters (warm air systems) performed adequately for a limited frost year, without any yield and income loss. However, there is 16,6% and 33,3% to 50% yield and income loss for a light and heavy frost year for the apple crop, and a 2% and 4% to 10% yield and income loss for a light and heavy frost year for the pear crop respectively. Besides, heaters require a high energy consumption and a high operational cost (FAO, 2005), leading fruit growers to switch to other more profitable methods in the medium and long term.

Moreover, for the two crops analyzed, Jonagold apple and Conference pear, the frost protection method with the best performance based on the yield and income obtained was the top crown irrigation. The results show no loss on the yield and income in any of the three frost-year cases. For this reason, sprinklers are one of the most used frost protection methods. It is the most effective method of protecting the crop, and its energy consumption and operational cost are considerably less than the used with heaters. Moreover, growers utilize under-tree sprinklers to run large blocks (5+ acres) of water at 40 plus or minus gallons/minute/acre. The heat and humidity generated to give an additional 2° (1.1° C) of temperature lift to an area of two hectares using 375 liters/minute/hectare (Orchard-Rite, 2021). However, the main disadvantages of the top crown irrigation method are the high installation cost and the large amounts of water needed. In many instances, limited water availability restricts the use of sprinklers (FAO, 2005); this is the case in many regions in the Netherlands where there is not enough fresh water available for frost protection purposes, as was pointed out in section 2.2.

Lastly, the wind machines didn't present any loss for a limited frost year, a 16,6% and 33,3% yield and income loss for a light and heavy frost year for the apple crop, and a 2% and 4% yield and income loss for a light and heavy frost year for the pear crop respectively. Although the results were similar to the frost buster heater, the wind machines provide more mid to long-term advantages that make them more rentable for farmers than the heaters. For instance, the operational cost and the energy consumption are lower than the required by the heaters. On the other hand, the wind machines are less effective than the top crown irrigation method during heavy and light frost years; however, the initial cost is much higher than wind machines, and the water resources availability is a constraint for the sprinkling.

In conclusion, although the initial investment is high (e.g., about $ 20.000 per machine), wind machines generally have lower labor requirements and operational costs than other methods (FAO, 2005). Therefore, in the case of dutch fruit producers located in regions with limited freshwater availability, it is recommended to select wind machines as their fruit frost protection method.

2.3.2 Costs-Benefit analysis of wind machines for frost protection

The Cost-Benefit analysis includes approximated values provided mainly by the online tool FROSTInno and the literature; these values are based on the frost protection equipment markets.

Table 3 indicates the general costs of wind machines per hectare; the cost includes the initial investment cost and the yearly consumption cost. The initial investment cost is a general value that varies depending mainly on the wind machine type (see section 3.1.3), the energy source, and the model's condition to be purchased. For instance, wind machines cost in the range of € 8,000 for a reconditioned model to € 30,000 for a new model (County, 2021). Although the initial cost can be high, the prolonged lifetime of the wind machines (30 years) and its suitable coverage range make this method profitable in the medium and long term.

Table 3 Wind machines cost measure(KCE & Proefcentrum Fruitteelt VZW, 2021)

Description	Value	Unit
Investment Cost		
Lifetime	30	Year
Purchase	8.000,00	€ / ha
Installation, operartors, equipment	12.000,00	€ / ha
Range wind machine	6	ha/device
Consumption costs		
Limited frost year	542,17	€ / (ha*year)
Light frost year	542,17	€ / (ha*year)
Heavy frost year	542,17	€ / (ha*year)

Moreover, over time the consumption cost is the same regardless of the frost year type. This yearly cost includes the operation, maintenance, and labor per hectare. However, as well as for the investment cost, the value can vary depending on the wind machine type, the energy source, and the wind machine's condition.

Table 4 Wind machines revenue/benefit measure (KCE & Proefcentrum Fruitteelt VZW, 2021)

Description	Limited frost year	Light frost year	Heavy frost year	Unit
Gross additional revenue	1.312,50	5.250,00	5.250,00	€ / (ha*year)
Net additional revenue	770,33	4.707,83	4.707,83	€ / (ha*year)
Payback time	16,23	2,66	2,66	year

Table 4 presents the revenue or benefits obtained from implementing wind machines as a fruit frost protection method. The revenue mainly depends on the frost year type; the income would be less in a limited frost year because the crop would not need a frost protection method. In the other cases, the light and the heavy frost years, the gross and net additional revenue is the same and higher than for a limited frost year. Likewise, the payback time would depend on the frost year type, in which it would be faster to recover the money invested for a light or heavy frost year than for a limited frost year that would take approximately six more times.

Furthermore, comparing the yearly consumption cost versus the yearly net additional revenue, the benefit was higher than the cost for all frost-year cases. For a limited frost year, the cost-benefit difference was € 228,16 in favor. In contrast, the revenue was almost nine times the cost for a light or heavy frost year, showing that the wind machines are profitable for protecting fruit crops from frost damage.

2.3.3 Potential benefits and limitations for clients

Although wind machines have been one of the most frequently used methods, given their proven effectiveness, their high investment and its operating costs often limit their purchase depending on the client. Based on what is presented in section 2.3.2, acquiring a wind machine is justified in orchards with high net earnings, where the likelihood of frost damage is at least once every five years, or on sites with a high frequency of light or heavy frosts (Beyá-Marshall et al., 2019). Therefore, producers with less profitable fruit crops are severely affected in case of a high frequency of light or heavy frost. Although they are potential wind machines clients, they probably wouldn't afford the investment cost. For this reason, some competitors in the fruit frost protection market have been accelerating the amortization of a wind machine providing financial solutions and keeping the guarantee of the equipment for several years (see Table 6), which is relevant for this type of client.

Furthermore, another limitation for a client is the environmental impact due to noise, being one of the most significant disadvantages of frost protection with wind machines. Although these machines work an average of 8 nights per year, 5 hours per night, noise is a significant restriction to obtain a permit (Ghentsupply, 2020). However, many new models come with a noise cancel system solving this environmental issue. Likewise, some potential clients refrain from purchasing a wind machine because it affects the landscape of their fields. To solve this inconvenience, the wind machines market offers portable or mobile wind machines that can be removed from the area after the frost event or the folding tower wind machine, which lets the client fold the anti-freezing tower after the frost event.

In conclusion, over time, the wind machine market has become flexible in solving many problems of its performance and esthetics. It has also become more reachable to all kinds of clients. Besides, wind machines are available when needed and can be programmed to start and stop as conditions change. And, they do not affect the growing conditions and, if the clients prefer, it can be moved to new blocks when replanting takes place.

2.4 Competitiveness analysis

This paragraph gives an overview of potential investors and competitors to estimate where the added value of wind machines can be found.

2.4.1 Market survey potential clients

Table 5 shows several potential investors or clients of wind machines as a fruit frost protection method. Most of these potential clients are companies that a vast part of its market is fruit production (apples and/or pears), and distribution in the regions identified in section 2.2 as critical for the sprinkling as a fruit frost protection method.

Table 5 Potential investors/clients for analyses.

Company / Investor	Description
Vogelaar Vredehof	**Vogelaar Vredehof** The Vogelaar Vredehof company is committed to ensure the customer quality apples and pears every day. It is a business that has grown from a cultivation company to an international trading and packaging company, leading in the industry thanks to its committed and expert employees and modern machinery. **Location: Zeeland province, The Netherlands** **Stakeholder Type: Potential client** **Website: https://www.vogelaar.com/nl**
GROWERS packers	**Growers packers** Growers Packers has an ongoing commitment to high quality, choice, price, and services. With over 25 years of experience, the company has a mission to bring optimum quality to the customers with a "First time Right, every time" mentality. It offers several fruits in its catalog and exceptional attention to the raspberries, blueberries, conference pears, and strawberries. **Location: Zeeland province, The Netherlands** **Stakeholder Type: Potential client** **Website: https://www.growerspackers.com/**
Handelsmaatschappij JAN OSKAM BV	**Handelsmaatschappij Jan Oskam BV** Handelsmaatschappij Jan Oskam BV is an import and export company of fruit, vegetable, and citrus products, whose core activity is to export its apples and pears from Dutch soil. With more than 65 years in the fruit and vegetable sector, they are one of the oldest independent fruit and vegetable export companies in the Netherlands. **Location: Utrecht province, The Netherlands** **Stakeholder Type: Potential client** **Website: http://www.janoskam.nl/**

	Zeeuwse Zonnekers The Zeeuwse Zonnekers with its orchards (25ha) is located on the separation of Walcheren and South Beveland. These islands are characterized by young marine clay, and it is rich in lime and other unique minerals that are indispensable for the growth of fruit trees and from which delicious fruits can naturally grow. The orchards mainly produce cherries, but also apples, pears, plums, and strawberries. These fruits are picked, stored, and packed with care. **Location: Zeeland province, The Netherlands** **Stakeholder Type: Potential client** **Website: https://www.zeeuwsezonnekers.nl/**
	Expotrade Holland BV Expotrade Holland B.V. is a grower-based international importer and exporter of fresh fruits and vegetables and is located in Europe's Largest Cooperative Auction House for fruits and berries – Fruitmasters Veiling, Geldermalsen. Their product range covers the entire spectrum of Dutch fruits and vegetables, among which the most basic are pears, apples, peppers, eggplants, tomatoes, berries, and salads. **Location: Gelderland province, The Netherlands** **Stakeholder Type: Potential client** **Website: http://www.expotrade-holland.nl/**
	Zeelandfruit Quality, competitive prices, and the best service Own cultivation, own sorting line, various packaging is possible **Location: Zeeland province, The Netherlands** **Stakeholder Type: Potential client** **Website: http://www.zeelandfruit.nl/**

2.4.2 Potential wind machines competitors

The potential competitors that can undertake the wind machine market for fruit frost protection, in general, are relatively small in the Netherlands. However, several overseas potential competitors have the expertise to supply wind machines for fruit frost protection and their services to the potential Dutch clients identified in section 2.4.1. Table 6 presents some of the potential wind machines competitors.

Table 6 Potential wind machines competitors for analyses

Company / Competitors	Description
	Agrofrost The Agrofrost company offers a wide range of frost protection machines. Depending on the client's needs, they can provide the solution that works best for them. Some of the fruit frost solutions they provide are FrostGuards Revolution & Basic, Trailed and 3-points Frostbusters, Frost Alarms, Mobile Wind Machines, Wind Machines, Burners. **Main location: Belgium** **Stakeholder Type: Potential competitor** **Website: http://www.agrofrost.eu/**
	RN7 Agri Services RN7 Agri Services has 15 years of experience in antifreeze towers, vine and arboriculture antifreeze towers, arboriculture antifreeze control devices. This company studies the market, installs, and does the maintenance of all types of antifreeze equipment. They have integrated project studies. Moreover, they offer their clients financing solutions in partnership with French banks. Their business is all around France, Benelux, and Switzerland. **Main location: France** **Stakeholder Type: Potential competitor** **Website: https://www.wind-machine.com/**

	Orchard-Rite Orchard-Rite is an original equipment manufacturer that puts innovation to work for its clients. They set the industry standard for producing the highest quality and most innovative tree shakers and wind machines. Moreover, they have distributors located worldwide ready to help the clients discover, purchase, and service Orchard-Rite products. **Main location: United States** **Stakeholder Type: Potential competitor** **Website: https://orchard-rite.com/**
	Schillinger Schillinger Company, headquartered in the South of Germany, as Tow & Blow Distribution Europe responsible for the complete area of Western and Eastern Europe to provide wind machine services as a frost protection method. **Main location: Germany** **Stakeholder Type: Potential competitor** **Website: /www.schillinger-beregnungsanlagen.de/**

2.4.3 Potential drone services competitors

Table 7 identifies several competitors that can provide monitoring services with drones to fruit producers in the Netherlands for assessing fruit frost impact and frost methods performance.

Table 7 Potential drone services competitors for analyses

Company / Competitors	Description
	HiView HiView deploys various platforms on which various sensors (both in the visible and non-visible parts of the spectrum) can be mounted. Raw data is converted to information using multiple state-of-the-art software packages. Information is transferred to knowledge by our highly qualified scientific staff. **Main location: Netherlands** **Stakeholder Type: Potential competitor** **Website: https://www.hiview.nl/**
	Remotely Piloted Aircraft System Services RPAS Services, founded in 2015, provides services to different market segments using unmanned aircraft technology. Moreover, it provides pilot services in the industry, agricultural and logistic environments. **Main location: Netherlands** **Stakeholder Type: Potential competitor** **Website: http://www.rpas-services.nl/**
	Smart Inspection Smart Inspection is a company that provides our customers with high-quality data and digital reports for industry-specific solutions with the help of innovative technologies (UAV, image processing, AI). We help our customers to save time and money. **Main location: Germany** **Stakeholder Type: Potential competitor** **Website: https://www.smartinspection.eu/**
	Pilot on Demand Pilot on Demand is a company that offers a wide range of services that perfectly match any project. The team can equip their drones with various cameras and sensors or payloads. The flexible property of the platform ensures that they can respond ideally to the client's wishes. **Main location: Netherlands** **Stakeholder Type: Potential competitor** **Website: https://pilotondemand.nl/**

	Dronematica Dronematica mainly deals with thermal and visual inspections with drones. They inspect a drone from bridges to solar panels with both thermal and high-resolution zoom cameras. A diverse range of end products is possible, such as a report in PDF, an orthomosaic, a 3D model, or just the images so that you can analyze yourself. **Main location: Netherlands** **Stakeholder Type: Potential competitor** **Website: https://dronematica.nl/**

3 Technical feasibility

3.1 Literature research

3.1.1 Description

Wind machines generally consist of a steel tower with a large rotating fan near the top (see Figure 10). There is usually a two- or four-blade fan with a diameter typically varying from 3 to 6 m that rotates around the tower with one revolution every four to five minutes. Most wind machine fans blow at a slight downward angle (e.g., about 7 °) in the tower direction, which improves their effectiveness. Besides, the typical height for fans is approximately 10-11 m above ground level. However, lower heights are used for lower canopies. Therefore, the fan height selection depends on the crop due to is set to avoid hitting the trees (FAO, 2005).

Figure 10 Wind Machine (Retrieved from Ghentsupply, 2020)

The power required to operate the fan usually comes from an engine mounted at the tower's base; however, some of the older machines have engines that rotate with the fan at the top of the tower (FAO, 2005). Furthermore, The local temperature response depends on the radial distance and the height above the surface of the wind machine (Heusinkveld et al., 2020). Therefore, the wind machine's configuration through the protected crop is essential, as well as matching the rotation of fans around their towers so that all fans are blowing in the same direction is believed to improve mixing effectiveness (FAO, 2005).

3.1.2 Operation theory

Wind machines mainly protect the crops from night frost damage by mixing the cold air near the plants with warmer air (Ribeiro et al., 2006) by increasing the downward sensible heat flux density and breaking up microscale boundary layers over the plant surfaces (FAO, 2005). Figure 11 shows that wind machines pull warm air down from high above a field, blow it downward and outward, push away cold air near target crops, and replace it with warmer air (Fraser et al., 2008).

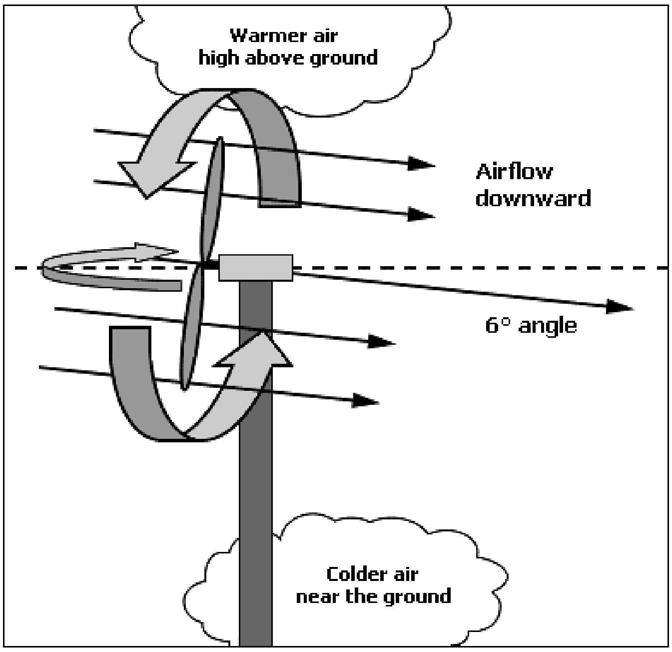


Figure 11 Wind machines operation (Fraser et al., 2008)

The fans protect against frosts even when there is no temperature inversion over the crop. This inversion occurs because, as the ventilation increases, the depth of the boundary layer on the leaf surface, the bud or the fruit, is reduced and favors sensible heat transfer from the air to the surface (Beyá-Marshall et al., 2019). Likewise, they work best when there is a robust thermal inversion layer, and vertical mixing results in an appreciable temperature change over a reasonable area within a crop (Ribeiro et al., 2006).

The wind machines effectiveness and protection range depend mainly on the degree or strength of thermal inversion that corresponds to a temperature differential between 15 m and 1.5 m: $T_{15} - T_{1.5}$. Moreover, the increase in air temperature that can be reached varies between ¼ and ½ of the temperature difference (thermal inversion strength) between T_{15} and $T_{1.5}$ (Beyá-Marshall et al., 2019). For instance, using a typical machine, 10 m in height and 130 kW of power, approximately the temperature increases between 25% to 50% of the inversion strength ($T_{15} - T_{1.5}$) that can be achieved in areas of 3 to 5 ha (Heusinkveld et al., 2020).

3.1.3 Product descriptions in the sector

Several wind machine types can combat the fruit frost in the market, and depending on the producer's needs (crop type, cost, necessity), the adequate one should be selected. The following are three different types of wind turbines that are available on the market:

<u>Fixed Antifreeze Tower</u>

Compact and quick to install with a protection range up to 7.5 ha. Usually, this wind machine type has around 10.7 meters in height (plus the base height). The base is made of a concrete volume of more or less five m^3, following the international building code. Besides, there are fixed antifreeze towers with two and three blades mainly made of solid composite fiberglass.

Figure 12 Fixed Antifreeze Tower

<u>Mobile Antifreeze Tower</u>

With a wide range of mobile and folding towers, suitable for all types of terrain in plains, valleys, or mountains, these mobile antifreeze towers are trending in markets with a protection range for up to 4 ha. Although the mobile antifreeze towers have a less protection range than the stationary ones, these have some benefits that can interest several producers. The following are the advantages of mobile antifreeze towers identified by the wind machines producer and distributer Orchard-Rite company:

- It can be used in multiple crops, leased land, or crops that need protection in various seasons.
- It keeps the field view free of machinery
- It can be used to dry the crop to accelerate harvest or prevent diseases
- It easily adjusts the protection patterns to focus on trouble spots

Figure 13 Mobile Antifreeze Tower

A portable or mobile wind machine (PM) can suit clients with a less profitable fruit crop. Due to the PM not requiring installation costs, fuel consumption (gasoline or diesel) is less than a stationary wind machine (SM). It can be used in other production processes in frost-free periods. However, the PM is less effective at controlling frost damage than the SM, both instability and coverage, spatially and vertically, as well as in temperature increase (Beyá-Marshall et al., 2019)

Folding Antifreeze Tower

This folding antifreeze tower is easy to install without a crane and folds down once the season is over. It has a protection range of up to 6 ha. The most significant benefit of this wind machine model is its integration into the landscape. Due to its mechanism that allows the tower to go down when the antifreeze tower is not working, the farmer can keep the landscape of its field clean of machinery and just pull it up when required.

Figure 14 Folding Antifreeze Tower

3.2 Thermal Flying Sensor literature research

3.2.1 Thermal cameras for flying sensors

Currently, thermal cameras are commonly used in agriculture to monitor and detect several parameters that can help maintain the crop in suitable conditions. One of the applications of thermal cameras and flying sensors in agriculture is detecting fruit frost damage and monitoring the performance of frost protection methods, such as wind machines. Table 8 presents some of the latest thermal cameras for flying sensors. The brands that stand out the most are FLIR and DJI, being FLIR, a company dedicated to the production of thermal cameras for several industry types. And DJI is a company that develops flying sensors and their complements as RGB, video, and thermal cameras.

Table 8 Thermal cameras for flying sensors

Product	Description
	**Mavic 2 Enterprise Advanced** The Mavic 2 Enterprise Advanced is DJI's compact showpiece. The compact Mavic 2 is equipped with a powerful thermal imaging camera with a 640 x 512 pixels thermal resolution accuracy of + - 2 degrees. **Company: DJI** **Website:https://www.warmtebeeldcamera.nl/en/mavic-2-enterprise-advanced.html**
	**Mavic 2 + Thermal Gimbal** DJI Mavic 2 drone with a thermal gimbal. Place a Flir thermal imaging camera underneath, and you can fly stabilized. **Company: DJI + FLIR** **Website:https://www.warmtebeeldcamera.nl/en/dji-mavic-2-thermal-gimbal.html**
	**FLIR VUE TZ20** The FLIR Vue TZ20 plug & play payload is compatible with the DJI V2 M200 series and M300 drones. This drone camera has a Wide FOV of 95º, a Narrow FOV of 35º, and 20x zoom. **Company: FLIR** **Website:https://www.warmtebeeldcamera.nl/en/flir-vue-tz20.html**

	**Zenmuse XT2 336 9HZ Radiometric** The Zenmuse XT2 336 9Hz has a frame rate of 9Hz and is available with three different lens options. A FLIR thermal imaging camera combined with a 4K camera and stabilization and machine intelligence technology from DJI. **Company: DJI + FLIR** **Website:https://www.warmtebeeldcamera.nl/en/zenmuse-xt2-336-9hz-radiometric.html#product-specificaties**
	**FLIR DUO PRO R 336** The FLIR Duo Pro R combines a high resolution, radiometric thermal imager, 4K color camera, and a full suite of onboard sensors to bring you the most powerful dual-sensor imaging solution in the world for small commercial drones. **Company: FLIR** **Website:https://www.warmtebeeldcamera.nl/en/flir-duo-pro-r-336.html**

3.2.2 Operating principles of thermal imagery

Thermal images are visual displays of measured emitted, reflected, and transmitted thermal radiation within an area (Berg, 2016). The operation of thermal imaging systems is based on the perception of the temperature differences between an object against a background and converting that difference to a visible image (Pulsar, 2020). Due to multiple thermal radiation sources, thermal imaging can be challenging depending on the object's properties and surroundings. The amount of radiation emitted by the object depends on its emissivity. Moreover, the camera itself emits thermal radiation during operation. For measuring thermal radiation, all these effects need to be considered. At short distances, atmospheric effects can be disregarded. But for greater distances from aircraft, it is crucial to consider atmospheric effects if temperatures are measured correctly (Berg, 2016).

On the one hand, for agricultural purposes, thermal cameras can produce images with few distortions during darkness and/or difficult weather conditions (e.g., fog/rain/snow). This is because a thermal camera is sensitive to emitted radiation, even from relatively cold objects, unlike a visual camera that measures reflected radiation and thus depends on illumination (Berg, 2016). Therefore, the thermal cameras are suitable for monitoring fruit crops during a frost event and provide reliable data.

On the other hand, t Thermal cameras are expensive and have low resolution compared to visual cameras. State of the art is currently 1344x784 pixels, and increased resolution comes with a higher price tag, up to e200000. Prices depend on the choice of the detector (cooled/uncooled, MWIR/LWIR) and optics. In comparison to a visual camera, a thermal camera typically requires more training for correct usage. The operator needs to know the physical principles and phenomena commonly viewed in thermal imagery to provide accurate measurements. The emissivity and reflectivity of different materials and the impact of the atmosphere are shown in Figure 15 (Berg, 2016).

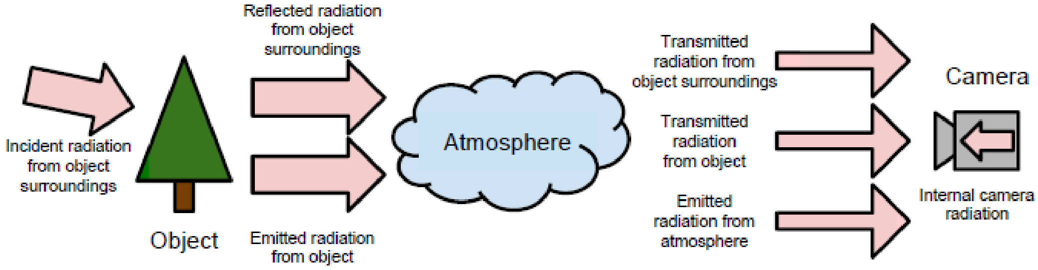


Figure 15 Influences on what the thermal camera measures (Berg, 2016)

3.2.3 Processing and interpretation of thermal images

Thermal images are a specific data source that is closely influenced by human perception of visual information. Compared to visual (RGB) cameras, thermal cameras with a small resolution and adverse factors (non-uniform and complex background)) make the target detection and identification challenging to perform. Even though using an optimal thermal camera setting (correct temperature range, focusing, and framing the desired sector of monitored space) cannot be granted a successful detection. Therefore, it is essential to implement methods and algorithms of digital image processing to provide optimal viewing parameters for processing thermal images (Sosnowski et al., 2018).

Likewise, the image processing algorithm should be focused not only on improving the perceived quality of an output image but also on the algorithm's computational complexity, which directly translates into the final rate of displaying the processed image sequence at the system's output. Moreover, to improve thermal imaging quality, it is necessary to apply dedicated algorithms that consider specific features of a thermal image (Sosnowski et al., 2018). Several software includes these algorithms as part of their image processing package that the user can implement to produce reliable outputs from the thermal images taken at the field, as Agisoft Metashape and Pix4D. These software are compatible with data provided by drones, RGB, and Thermal images and can correct them to obtain better quality. Besides, if there is sufficient data with the correct georeference and overlapping, there is the possibility to produce thermal maps that can better visualize the study area.

4 Experimental development

4.1 Data acquisition

An experiment was carried out using drones with a thermal camera installed to analyze the impact of wind machines in fruit crops as a frost protection method. The drones allow taking images from a top view of the crops using different camera types depending on the scope of the experiment. In this particular case, thermal cameras were used to detect the crops' temperature behavior with the influence of a wind machine. Figure 16 shows the data acquisition process done by FutureWater and HiView in the field.

Figure 16 Field measurement of the Krabbedijke pear orchard during night frost

4.1.1 Study area and setup

The data acquisition took place in a pear tree plantation farm located in the Krabbendijke region in Zeeland. This region is a farming province characterized for having yielded hundreds of hectares of fertile soil, in which almost 5% of the crops correspond to stone fruit and pomes (apples and pears) (Broodman, 2012). Besides, the assessed pear orchard belongs to the Vogelaar Vredehof company that produces and supplies quality apples and pears. Krabbendijke is the company's head office, strategically situated in one of the significant fruit-growing regions in the southwest of the Netherlands, between Rotterdam, Antwerp, and Vlissingen ports. Currently, Volgelaar Vredehof is using wind machines as a fruit frost protection method in early spring. Therefore, it is a strategic area to evaluate the impact of wind machines defense during night frost periods.

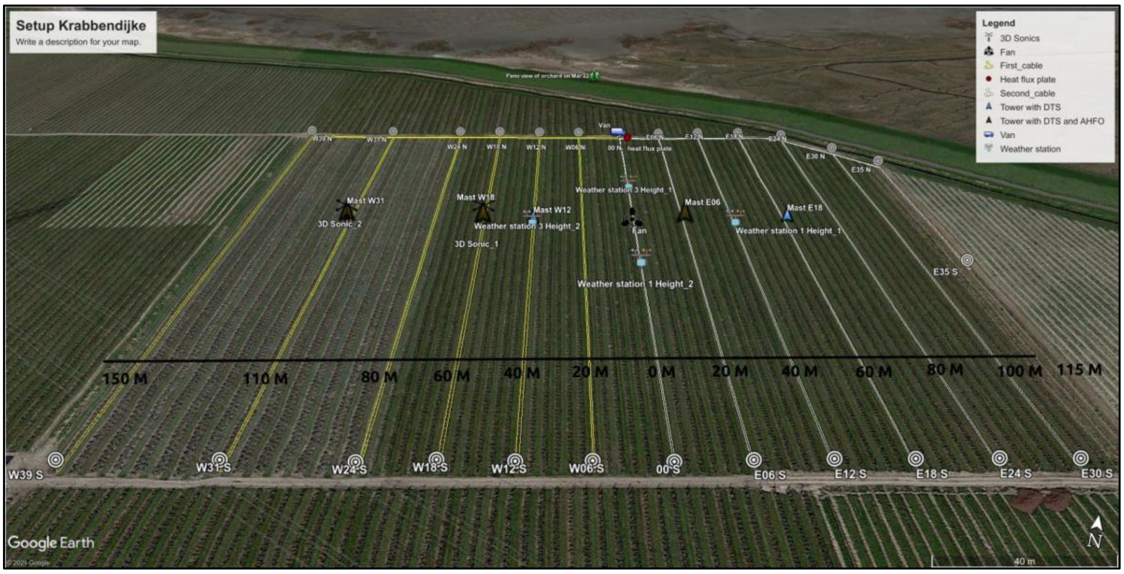


Figure 17 Setup Krabbendijke

Figure 17 presents the setup of the assessed farm based on the wind machine radius. Furthermore, the data acquisition was executed in the early hours of 14 April 2021 in "clear sky conditions". Therefore, it didn't necessarily have to be freezing for obtaining the data because the primary purpose was to have a clear vertical temperature profile between the crop and the drone.

4.1.2 Equipment

Unmanned Aerial Vehicle (UAV)

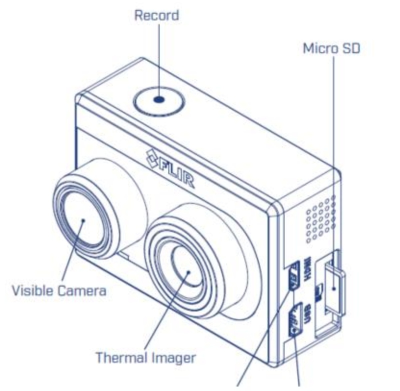
The unmanned aerial vehicle used for this practice was the DJI Mavic 2 (Figure 18), a small compact device with enormous potential for fieldwork. DJI Mavic 2 Pro, featuring the collaboratively developed Hasselblad L1D-20c, brings innovative experiences to the field with advancements in drone photography and UAV photogrammetry. The Hasselblad L1D-20c allows the user to obtain a higher standard for aerial image quality. A fully stabilized 3-axis gimbal with its powerful 20MP 1" sensor offers improved lowlight shooting capabilities compared to other drone cameras. Moreover, the remote controller works at both 2.4 GHz and 5.8 GHz; due to the unique transmission technology developed by DJI Company, it is possible to transmit data up to a distance of 8 km and can display video from the UAV on the mobile device with a resolution up to 1080p (Alfio et al., 2020).

Features	Specifications
UAV Platform	
Max. take-off weight	907 g
Maximum Speed (P-Mode)	48 km/h/13.4 m/s
Flight time	~31 min
Camera: Hasselblad L1D-20c>	
Sensor	1″ CMOS; Effective pixels: 20 million
Photo size	5472 × 3648
Focal length	10.26 mm
Field of view	approx. 77°
Aperture	f/2.8–f/11
Shooting speed	Electronic shutter: 8–1/8000 s

Figure 18 Mavic 2 aircraft specifications (Alfio et al., 2020)

Thermal camera

The camera used for temperature mapping was the FLIR Duo R, a compact, lightweight, radiometric thermal and visible light imager designed for professional UAV applications, as shown in Figure 19. A thermal imager measures the longwave infrared radiation received within its field of view. From this, the temperature of the object being measured can be calculated. Every object with a temperature above absolute zero emits infrared radiation. Thus, there is a correlation between body temperature and the intensity of the infrared radiation it emits. The FLIR Duo R pairs 160x120 thermal resolution using a Lepton thermal sensor with a 2-megapixel color and lowlight camera. With the R-package *Thermimage* (Thermal Image Analysis), the raw thermal sensor data is translated into a temperature image using the radiometric metadata stored in the image Exif tags and meteorological data collected by the TAHMO weather station (i.e., relative humidity and atmospheric temperature).



Overview	FLIR Duo R
Thermal Imager	Uncooled VOx Microbolometer
Sensor Resolution	160 × 120
Lens	57° × 44°
Spectral Band	7.5 – 13.5 µm
Thermal Frame Rates	7.5 Hz (NTSC); 8.3 Hz (PAL)
Thermal Measurement Accuracy	+/-5°C
Visible Camera Resolution	1920 × 1080
Visible Camera FOV	90°

Figure 19. FLIR Duo R camera used for thermal UAV mapping

The raw A/D bit signal from FLIR is stored in a 16-bit encoded value, ranging from 0 to 65535. This raw value is what the sensor detects, which is related to the radiance hitting the sensor. Each sensor was calibrated at the factory against a blackbody radiation source, so calibration values to convert the raw signal into the expected temperature of a blackbody radiator are provided. The most relevant variables to extract for calculating temperature values from raw A/D sensor data are listed in Figure 20, which can be subsequently used as input in the function *raw2temp* of the *Thermimage* R-package for conversion of raw values to temperature. The temperature conversion incorporates Plank's law and the Stephan Boltzmann relationship, atmospheric absorption, camera IR absorption, emissivity, and distance.

```
ObjectEmissivity<-  cams$Info$Emissivity             # Image Saved Emissivity - should be ~0.95 or 0.96
dateOriginal<-cams$Dates$DateTimeOriginal            # Original date/time extracted from file
dateModif<-   cams$Dates$FileModificationDateTime    # Modification date/time extracted from file
PlanckR1<-    cams$Info$PlanckR1                     # Planck R1 constant for camera
PlanckB<-     cams$Info$PlanckB                      # Planck B constant for camera
PlanckF<-     cams$Info$PlanckF                      # Planck F constant for camera
PlanckO<-     cams$Info$PlanckO                      # Planck O constant for camera
PlanckR2<-    cams$Info$PlanckR2                     # Planck R2 constant for camera
ATA1<-        cams$Info$AtmosphericTransAlpha1       # Atmospheric Transmittance Alpha 1
ATA2<-        cams$Info$AtmosphericTransAlpha2       # Atmospheric Transmittance Alpha 2
ATB1<-        cams$Info$AtmosphericTransBeta1        # Atmospheric Transmittance Beta 1
ATB2<-        cams$Info$AtmosphericTransBeta2        # Atmospheric Transmittance Beta 2
ATX<-         cams$Info$AtmosphericTransX            # Atmospheric Transmittance X
OD<-          cams$Info$ObjectDistance               # object distance in metres
FD<-          cams$Info$FocusDistance                # focus distance in metres
ReflT<-       cams$Info$ReflectedApparentTemperature # Reflected apparent temperature
AtmosT<-      cams$Info$AtmosphericTemperature       # Atmospheric temperature
IRWinT<-      cams$Info$IRWindowTemperature          # IR Window Temperature
IRWinTran<-   cams$Info$IRWindowTransmission         # IR Window transparency
RH<-          cams$Info$RelativeHumidity             # Relative Humidity
h<-           cams$Info$RawThermalImageHeight        # sensor height (i.e. image height)
w<-           cams$Info$RawThermalImageWidth         # sensor width (i.e. image width)
```

Figure 20. Variables for calculation of temperature values from raw A/D thermal sensor data

4.1.3 UAV flights

FutureWater and HiView were on site to conduct UAV flights to collect data in the RGB and thermal spectrum, which were used to obtain the soil and vegetation's thermal properties (i.e., sensible heat flux). Eight flights were conducted to obtain the thermal performance over time. All the flights followed grid paths to have a complete overview of the farm in which it can be taken the most significant area of the wind machine influence radius, as shown in Figure 21.

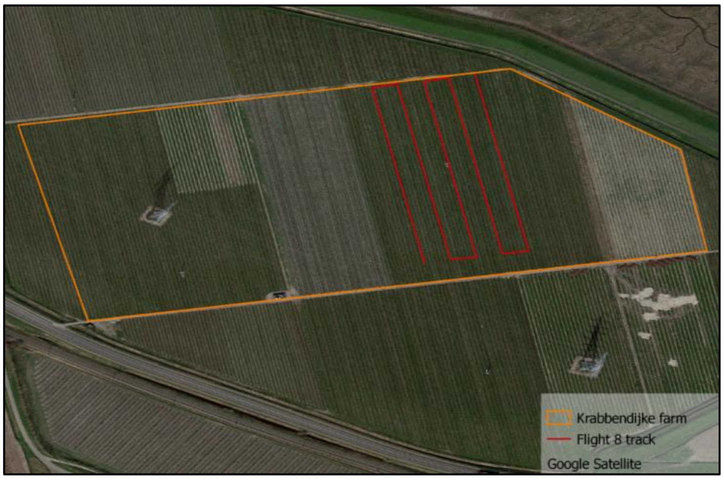


Figure 21 Flight No.8 track and farm area

The flights were carried out early in the morning, between 5 and 8 am, performed with the DJI Mavic 2 aircraft, and installed the FLIR Duo R camera. Moreover, as shown in Table 9, complementary information was registered to support the measurements and further analysis.

Table 9 Flights log and complementary measurements

Flight Number	1	2	3	4	5	6	7	8
UAV flying position	Top view	Top view	Top view	Top view	Top view	Top view	Top view	Top view
Starting time	5:15 hrs	5:23 hrs	5:58 hrs	6:33 hrs	6:47 hrs	7:00 hrs	7:33 hrs	7:42 hrs
Soil temperature	0,13 °C	0,11 °C	-1,0 °C	-	-0,06 °C	-	-	0,02 °C
Ventilator	Activated	Activated	Not Activated	Activated	Activated	Not Activated	Not Activated	Not Activated

4.2 Output and visualization

4.2.1 Data analysis

A detailed analysis was done with the measurements taken during Flight No. 8 because it presented the most precise data recollected during the practice. Moreover, the study was performed for the images aligned with the wind machine, as shown in Figure 22. For selecting the points to be analyzed, the wind machine was set as a reference point represented with the "0m". From there, the points at 50 and 120 meters north and south were chosen.

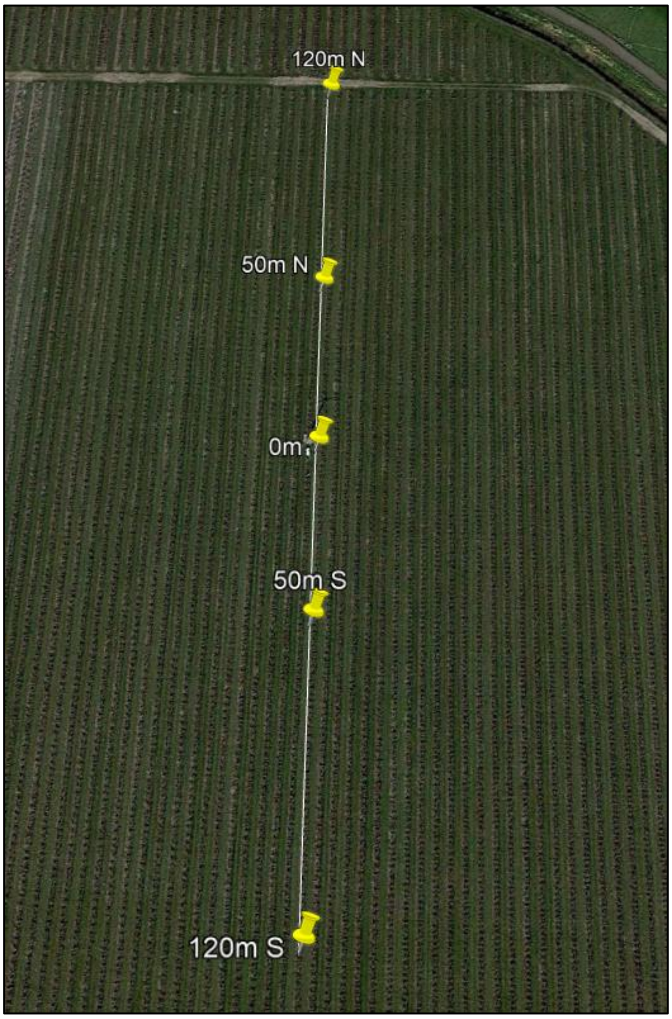


Figure 22 Locations of the images analyzed

For the analysis, the computation was done using the open-source software QGIS. Firstly, 250 random points were generated through the entire image as a vector layer. Secondly, using the "Point Sample Tool" plugin, the temperature values were extracted. Lastly, the data were exported to Microsoft Excel for further processing, and the computation of the histogram was carried out using the Data Analysis complement.

4.2.2 Results

Figure 23 shows the histograms of the locations analyzed based on the temperature of the canopy cover and the frequency. It has to be considered that the wind machine was switched off more than an hour ago for the moment of the data acquisition of the flight analyzed (number 8) (see Table 9). Therefore, the temperature values obtained are lower than those expected when the wind machine is actively working.

In general, considering the above, the wind machine kept the temperature above -1°C along the analyzed radius even after an hour of being switched off, which prevented the crops from reaching the critical temperature in most locations (see Figure 1). However, the image located 120 meters north of the wind machine presented the lowest temperatures, under -1°C, unlike the others. Moreover, the wind machine's north images showed lower temperatures than those from the south. This difference could be due to factors like a wind gust that could have hit the crop at the measurement moment, mainly at the northern part of the wind machine, causing a more considerable drop in the temperature.

Furthermore, the image that captured the wind machine (0 meters) presented more uniformity in temperature than the other images. This phenomenon occurs because the temperature uniformity improves as the center (in this case, the fan) of the operating radius is approached, the exact reason why there is more temperature variability in the 50 and 120 meters images.

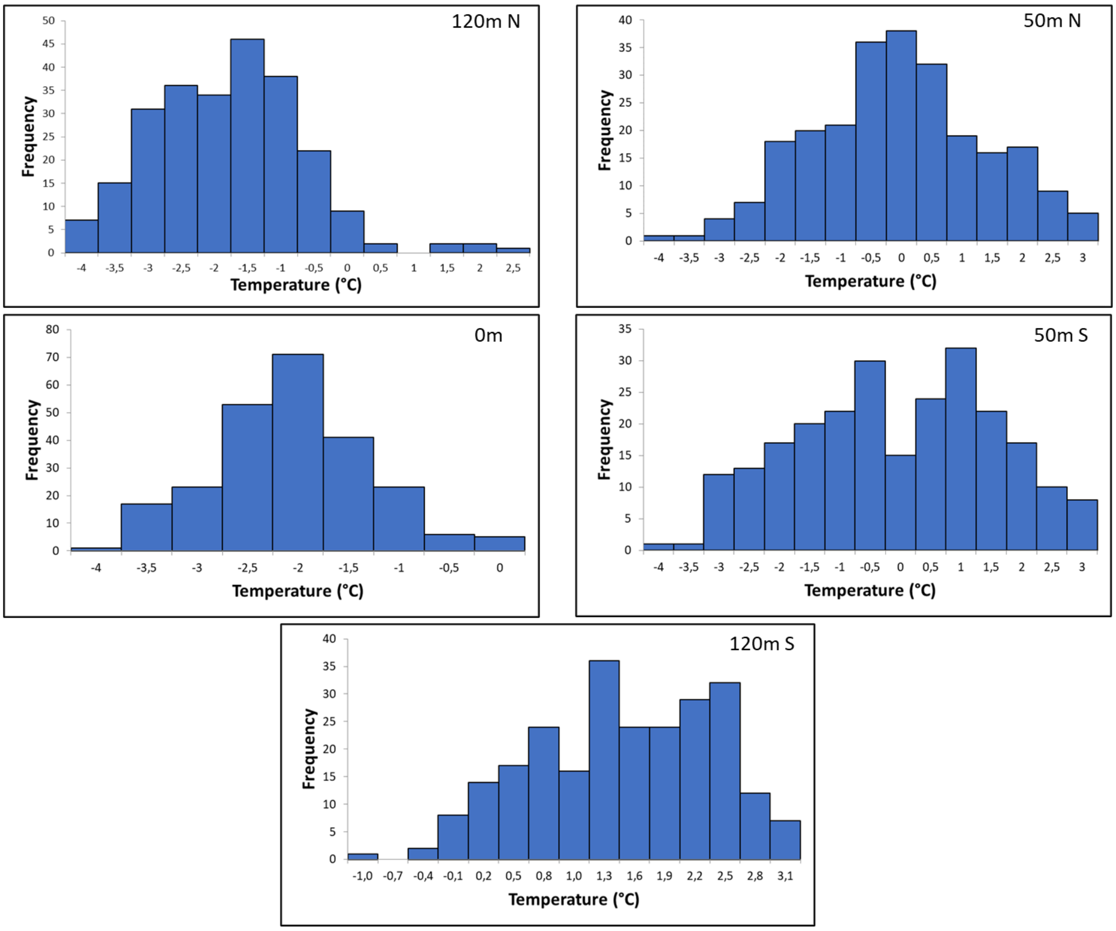


Figure 23 Temperature of the crop canopy cover vs. Frequency

For the case under analysis, pear crop, the critical temperature of -2°C that can damage up to 10% of the crop yield (see Figure 1) from stage 2 that corresponds to the budburst, was not reached in most of the images analyzed, except in the one at 120 meters from the wind machine. This risky drop in temperature could be due to the pear producer turned off the wind machine early when the crop was still at risk of being affected by the low temperatures. The producer can consider keeping the wind machine on until the risk reduces to prevent this yield drop hazard.

5 Conclusions and recommendations

5.1 Wind machines as a suitable frost protection method for Dutch fruit growers

Frost damage has been a frequent hazard for fruit growers in the Netherlands, getting worse within time due to climate change. For this reason, it is essential to look for alternatives that can ensure the economic stability of these farmers, reducing as much as possible the yield and income loss, and that can be sustainable alternatives depending on the environmental conditions. There are several frost protection methods that the Dutch fruit growers have been using, which the most popular one is sprinkling freshwater during a frost event. This frost protection method is the most effective, due to it instantly increases the temperature of the crop, protecting the bud and flowers from getting frozen, and based on studies, there is no yield and income loss. However, the main disadvantage is the large amounts of water needed that, in many instances, limited water availability restricts the use of this frost protection method.

Furthermore, the water availability limitation is common in several regions in the country. Not all Dutch waterboards have the water resources' capacity for providing freshwater to farmers for frost protection purposes. Many fruit growers are located in these regions where freshwater availability is a constraint. Agriculture is a low priority on the national water's priority list means that producers must look for complementary solutions. Given the above, the Dutch agricultural sector should look for sustainable alternatives to address the fruit frost damage without depending on natural resources.

Wind machines can be a more sustainable alternative than sprinkling freshwater for frost protection. It does not require the use of any natural resources, and its efficiency is satisfactory. Therefore, if the fruit growers select the wind machine as a frost protection method, in a light frost year, the yield and income loss would be a maximum of 16,6% for an average apple crop and 2% for an average pear crop. And they would also be contributing to the reduction of the environmental impact with agricultural practices.

From an economic perspective, a wind machine is also the best alternative for Dutch fruit growers. Although the initial investment cost is high, this frost protection method has lower labor requirements and operational costs than other frost protection methods. Moreover, wind machines' payback time depends on the intensity of the coming frost years. In the cases of light or heavy frost years, it is 2,66 years, recovering the initial investment rapidly. Following the global forecasting of climate change, the spring freezes are almost a certainty in any given year in the Netherlands, meaning that fruit producers should be prepared with a frost protection method and that investing in wind machines would be worthy.

In conclusion, wind machines are a suitable alternative for those fruit growers in the Netherlands located in regions where freshwater is limited. This frost protection method would prevent frost damage efficiently, is more sustainable compared to sprinkling, the operational and labor cost is low. It remains the same over time; its payback time is short, ensuring revenue to fruit growers over the years.

5.2 Flying sensor for monitoring the crop and frost protection method performance

Flying sensors are an excellent technology to monitor agricultural practices efficiently. Incorporating cameras and different types of sensors into UAVs allows assessing and computing several parameters that can help the timely decision-making. An aircraft with a thermal camera integrated for fruit frost damage assessment is ideal because the temperature is the most important parameter to analyze.

Two main aspects can be assessed from the data provided by the thermal camera for frost protection purposes: the crop temperature and the frost protection method's performance. The crop temperature monitoring could give an idea of how the surface temperature of the crop is behaving during a frost event. The temperature data would indicate which crop's zone is affected by the frost event and which is doing well for further assessment. Moreover, monitoring the frost protection method's performance can also be followed by the thermal data. It can be identified how much the temperature increases with the assessed method and the actual radius of influence. Hence, farmers and/or fruit companies can make timely decisions for future frost events with this information.

Furthermore, the Netherlands is a country that can benefit from monitoring agricultural practices with the use of flying sensors. It is a country that allows the regulated use of drones for research and technical purposes. Also, its topography is ideal for capturing top view data. Therefore, periodically incorporating the flying sensors assessment would be wise for fruit growers and companies to ensure the minimum economic loss due to frost damage.

Likewise, the flying sensor's data is stick to the data acquisition and manipulation by the operator. Therefore, proper protocols should be followed to have the necessary information for assessing the crop and frost protection performance. These protocols should consider that the thermal cameras don't have the same accuracy for capturing images as an RGB camera and are more susceptible to reduced image quality with movement. Hence, it is recommended to flight with a lower velocity than the one used for RGB data acquisition.

Lastly, to measure at a field level and not at point level as was done in this study, it is recommended to fly the drone, ensuring an exhausting overlapping between images. In this way, there is no missing information, and the images can be processed without any problem, having as an output a thermal map of the field. This thermal map presents practically and visually the crop's behavior and the frost protection method's performance.

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