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# Designing and Pricing Weather Index Insurance with Applications to Winter Wheat Production in Tartu County

Actuarial and Financial Engineering
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## Designing and Pricing Weather Index Insurance with Applications to Winter Wheat Production in Tartu County

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**Abstract.** In our study, we attempt to get the reader familiar with the concept of the weather index insurance (WII), also called weather index-based insurance, which is seen as an alternative to the traditional agricultural insurance products by many researchers (see, e.g., Daron and Stainforth (2014), Carter et al. (2015), Sibiko et al., (2018)). Furthermore, we provide information regarding the advantages and practical challenges of the WII concept and give and overview of the process of designing this type of an insurance product. The aim of our study is to design several policies against low temperature harmful to the winter wheat. Our numerical example is based on Tartu-Tõravere weather station. Pricing is based on hypothetical claim sizes data.

**Keywords**: daily average temperature, burn analysis, index modeling.

**CERCS research specialisation**: P160 Statistics, operation research, programming, actuarial mathematics

## Ilmaindeksipõhise kindlustuse disain ja hinnastamine talinisule Tartu maakonnas

Magistritöö

Evgenia Kichuk

**Lühikokkuvõte.** Käesolev uuring keskendub ilmaindeksipõhisele kindlustusele. Seda on soovitatud alternatiivina traditsioonilistele põllumajanduskindlustustoodetele (vt nt, Daron and Stainforth (2014), Carter et al. (2015), Sibiko et al., (2018). Uurime ilmaindeksipõhise kindlustuse eeliseid ning puuduseid. Anname ülevaate sellise toote kujundamisest. Esitame disaini ja hinnastuse Tartu maakonnas toodetava talinisu külmakahjustuste kindlustamiseks.

**Märksõnad**: päeva keskmine temperatuur, hinnastamine, kahjude modelleerimine.

**CERCS teaduseriala**: P160 Statistika, operatsioonanalüüs, programmeerimine, finants- ja kindlustusmatemaatika

# Contents

# 1 Introduction

Among existing economic sectors agriculture production is one of those where the process itself is characterized by a notable fluctuation of results. In particular, these fluctuations can be explained by the existence of high dependence of output on weather conditions that can consequently destabilize a farmer's income. Indeed, according to Janowicz-Lomott et al. (2015), farmers operating in developed and developing countries usually call adverse weather changes, volatility of market prices, legal and financial regulations and restrictions, personal issues, and technological inefficiency as the main challenges for them to cope with. Additionally, agricultural conditions and the level of development of the agricultural sector varies from country to country, e.g., irrigation is often not available in developing countries, making agricultural profits highly dependent on seasonal and temporal weather fluctuations, leaving the risk of inclement weather as a significant cause of income vulnerability and production inefficiency.

In spite the fact that modern technology has significantly boosted the speed and accuracy of meteorological forecasts, and that the number of meteorological stations has also increased, weather is still one of the most uncontrollable and important sources of risk for agricultural production. Ji et al. (2018) wrote that usually farmers make a lot of decisions "prior to the realization of weather, such as decisions on acreage, crop allocation, seed variety, planting time, and tillage method. These ex ante decisions are made based on subjective expectations over climate rather than the realization of weather." Due to global climate change, the weather fluctuation has been increasing and that makes farmers' climate expectations misleading and consequently jeopardizes their prosperity.

Following World Bank (2011), agricultural insurance is considered to be the most efficient tool of formal risk management for handling some of the agricultural risks, including those caused by unfavorable weather events. For agricultural purposes, insurance schemes based on claim sizes are aimed to cover multiple weather and non-weather (e.g., pests) related risks (also called perils or events). In traditional agricultural insurance, the compensation is based on an assessment of the amount of the insured's actual loss or the proof of a specific loss (International Fund of Agricultural Development (IFAD), 2017) . In other words, there is the need for insurer to assess a farmer's performance (either at the individual or regional level) so that the claim payouts are ascertained on the basis of output.

However, there are several challenges that make traditional claim-based insurance schemes covering risks in the developed countries infeasible for farmers from developing countries (Daron and Stainforth, 2014). Many research reports produced by, e.g., World Bank (2011) and International Fund for Agricultural Development (2010, 2017). are devoted to the study of agriculture and insurance in developing countries. These studies highlight that high premiums and low-speed of payouts are two of the main challenges of traditional insurance and that weather index insurance has the potential to increase availability and attractiveness of agriculture insurance for farmers.

In our study, we attempt to get the reader familiar with the concept of the **weather index insurance**, also called **weather index-based insurance**, which is seen as an alternative to the traditional agricultural insurance products by many researchers (see, e.g., Daron and Stainforth, 2014; Carter et al., 2015 and Sibiko et al., 2018). Furthermore, we provide information regarding the advantages and practical challenges of the weather index insurance concept and give and overview of the process of designing this type of an insurance product. Ultimately, the general purpose of our study is to describe two different approaches for pricing the weather index insurance product, i.e., historical and index modelling. We will suggest three different constructions of a claim size design, which are going to be based on average of average temperature (AAT) index and on the daily average temperatures (DAT) and, consequently, calculate the premiums for all those claim design constructions. For the sake of illustration, we will set hypothetical parameters to implement the historical approach and the index modelling approach for pricing weather index insurance product for winter wheat cultivated in Tartu county, Estonia.

The data that support the findings of this study are available from Estonian Weather Service of Estonian Environment Agency, but restrictions are applied to the availability of these data, which were used under license for the current study. Therefore, the data is not publicly available. Data are however available from the author upon reasonable request and with permission of Estonian Weather Service of Estonian Environment Agency.

## 2 The Concept of Weather Index Insurance

For the better understanding of the weather index insurance (WII) concept, we would like to start from providing definitions of the weather and climate. While **climate** is defined as the “long-term pattern of weather in a particular area,” National Geographic (2019), **weather** is “state of the atmosphere at a particular place during a short period of time. It involves such atmospheric phenomena as temperature, humidity, precipitation (type and amount), air pressure, wind, and cloud cover,” Encyclopædia Britannica (2019). According to International Fund for Agricultural Development (IFAD) (2010) “the concept of WII is not new: proposals for this type of insurance were first articulated by Halcrow (1948) and Dandekar (1977); The Australian Government commissioned a feasibility study of rainfall insurance in the mid-1980s, but decided not to pursue it (IAC 1986),” Jewson and Brix (2005) state that in the concept of weather derivatives, “the most commonly used weather variable is the temperature, as either hourly values, daily minima or maxima, or daily averages. Of these, daily average is the most frequently seen.” Following the terminology of papers related to agricultural insurance, above-mentioned weather characteristics can become a basis for **weather indexes** used for the purposes of WII. **Weather indexes** is the generalized measure of underlying weather variable(s) (Jewson and Brix, 2005), e.g., AAT, sum of activate temperatures (SAT), Heating-degree-day (HDD), weighted anomaly of standardized precipitation (WASP) index etc.

In general, the concept of WII is very similar to the concept of the weather derivatives: both of these concepts imply that an insured party will receive a payout when the weather event, specified in the contract, occurs. The weather event triggering the claim, in the framework of weather derivatives or WII, means that the weather index represents the weather-related risk for an insured party and is based on weather variables recorded in the reference weather station. The claim event occurs if the weather index falls below or rises above the trigger level that is pre-defined in the contract. Nevertheless, WII is more seen as a special case of agriculture insurance, while its construction is similar to weather derivatives, which are similar to financial derivatives.

However, for pricing WII, an actuary should construct the product’s design based on weather index which reflects some weather event as precisely as possible. Hence the design of WII requires actuaries to define additional parameters (trigger value, exit value, tick size, etc.) in order to set up the formula for a claim event and claim size, which are allowed to be based on single or on various weather indexes. Ultimately, in order for the underlying index to be a reliable proxy for loss, it has to be based upon an objective measure (e.g., cumulative level of precipitation) that exposes a solid correlation with the variable of interest (e.g. crop yield).

Ntukamazina et al. (2017) suggested index-based insurance products be divided into two main types: area yield index insurance[1] and weather index insurance, represented by index-based crop insurance and index-based livestock insurance. During this study we will mainly focus on the weather index-based insurance against losses of a crop yield.

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[1] “With this type of insurance, the indemnity is based on the realized (harvested) average yield of an area such as a county or district. The insured yield is established as a percentage of the average yield for the area (typically 50–90 percent of the area average yield). An indemnity is paid if the realized average yield for the area is less than the insured yield, regardless of the actual yield on a policyholder’s farm. This type of index insurance requires historical area yield data on which the normal average yield and insured yield can be established.” Source: `https://www.indexinsuranceforum.org/faq/what-are-different-types-%E2%80%9Ccrop%E2%80%9D-index-insurance`

## 2.1 Advantages

Weather index-based insurance products against crop losses are believed to be more effective in comparison with traditional insurance contracts by offering lower premiums and speeding up the payout process. In other words, the administration costs per policy of WII are lower than in traditional claims-based forms of insurance because there is no need for claims-handling and once the weather index is triggered by the related weather event, all insured farmers will receive a payment regardless of whether the loss was experienced or not. As a consequence, premiums can be lower and payouts can become more rapid, so this type of insurance provides an attractive alternative for small-holder farmers in developing countries (Bobojonov et al., 2014).

In comparison with traditional insurance, there is no risk of **adverse selection** while assessing the loss the insured has faced. Adverse selection describes the situation when farmers (who know that they have increasing risks in production process) have hidden information about their risk exposure, but the insurer has no access to this information (Carter et al., 2015). Hence those farmers feel encouragement to insure, because they know that it is likely that they will place a claim in the future and, as premiums are calculated on the average producer, they are likely to get a payout for a rather low premium. The concept of weather index insurance implies that all insured farmers within the defined area have the same insurance payout conditions, regardless of their specific risk exposure.

Another problem related with the hidden information occurs when farmers intentionally (in order to influence claims) act in a way to increase their exposure to risk. This behavior is called **moral hazard**. It makes the insurer exposed to higher levels of risk than had been anticipated when premium rate was established. With WII, all producers in a given area are treated equally, i.e., increasing risk exposure becomes pointless because there will be no loss assessment if the weather index established in the contract is triggered, so the problem of moral hazard is minimized.

WII is considered to be a more attractive insurance option for the farmers from developing countries, therefore it is highly important to educate them about the product. As this type of insurance product differs from traditional claim-based insurance, it is essential that the client has comprehensive understanding of how the indemnity is calculated and when it is due (International Fund for Agricultural Development (IFAD), 2010), what are the benefits of this type of insurance and that it insures against specific adverse weather event. Additionally, as the policyholder usually has a direct access to the information according to which the payouts will be calculated and received (weather forecast on TV or in the internet, different types of notification-messages) weather index-based insurance contract also suggests greater transparency (Zhang et al., 2017).

## 2.2 Disadvantages

Although WII products outclass traditional indemnity-based ones in some sense, insurers still have to overcome other challenges. In spite of the fact that there is no necessity to estimate farmer's losses, weather index-based insurance products are typically priced using historical weather data series to estimate the frequency and magnitude of prospective indemnity payments (International Fund of Agricultural Development (IFAD), 2017). Notable that availability of up-to-date as well as historical weather records and its quality is essential prerequisite condition for the construction of the weather index-based insurance product. Another important condition is that at least 20–30 years of internally consistent historical weather observations are needed for a proper actuarial analysis of the weather (e.g., Stoppa and Manuamorn, 2017). However, availability and quality of weather data can drastically vary from country to country. In developing countries, the deficiency of historical and real-time weather records is often a significant obstacle which can contribute to such poorly designed insurance contracts that they run the risk of becoming unreliable (International Fund of Agricultural Development (IFAD), 2017).

Zhang et al. (2017) emphasize that possible mismatch between farmer's loss and the weather index can lead to the increasing basis risk. Briefly, **basis risk** occurs when the disagreement between insurance payouts and actual losses occurs – either a payout is triggered even though there are no losses or there are losses but no payout. Causes of basis risk can be related to the size of the unit area of insurance (UAI) and quantity and dispersion of weather stations within the area (IFAD, 2017). Turning the focus to the UAI, it should be said that it is not so clear whether the insurer should let each farmer define it by himself/herself or there should be no option rather than to insure the whole area the farmer owns. Considering the issue of the geography of weather stations, Chen (2011) writes that the distance between an insurable area and a weather station should amount to "no more than 10 kilometers, but in developing countries a maximum of 20 or 50 kilometers is also accepted" for construction of WII products.

Although WII proposes new opportunities especially to farmers, many of whom are located in most vulnerable areas in the sense of weather risks (natural disasters), WII still can't be considered as a panacea. According to Xiao and Yao (2018), WII demonstrates better performance only when there is a close correlation between the weather index and the yield. Nevertheless, WII is less useful where crop production is impacted by many or complex causes of loss (as may be the case in the humid subtropics), or where pests and disease are substantive hazards to yield. For a given environment, other insurance products may be more appropriate such as area-yield index insurance or named-peril/multiple-perils crop insurance, i.e., traditional claim-based insurance (International Fund of Agricultural Development (IFAD), 2011).

## 2.3 Challenges

Agriculture being branch of the economy aimed at providing the population with food and providing raw materials for a number of industries, is highly exposed to climate changes. Weather related risks are hugely important for poor people in developing countries as an estimated two-thirds of them depend on agriculture and natural resources (FERDI, 2014). International Fund for Agricultural Development (IFAD) (2013) wrote the following about smallholder farmers from developing countries: “they manage approximately 80% of the world’s estimated 500 million small farms and provide over 80 per cent of the food consumed in a large part of the developing world.” Taking into account above-mentioned facts it can be said that the creation of effective and affordable insurance products based on weather indexes could have a significant impact on the well-being of farmers. In accordance with Greatrex et al. (2015) there are already “at least tens of millions” of farmers who hold index insurance products in the world. Nevertheless, “in environments where poverty traps are likely, simulations find that households just above the poverty line - those that insurance could feasibly help the most - are also the least likely to purchase insurance,” Janzen et al. (2013). Smallholder farmers in developing countries often lack access to agricultural insurance (International Fund for Agricultural Development (IFAD), 2010). Insurance companies tend to concentrate in urban cities and towns so that they often do not have networks in rural areas (World Bank, 2011).

Additionally, the obligation to pay all policyholders at once in case if the weather index specified in the contract is triggered can be overwhelming for local insurance companies, thus international reinsurers could enable them to transfer some of their risk. In reality there is a hesitation among the international reinsurance market to become involved with local insurance companies (Jensen and Barrett, 2016). Moreover, according to FERDI (2014) in the absence of adequate high-quality data (weather and crops yield), uncertainty-averse reinsurers place a large premium penalty on uncertainty. All of that makes the construction and further market penetration of WII a quite risky activity for local insurers. With the lack of protection against unfavorable weather events, rural households tend to self-insure, that ends up having high costs and limited effectiveness (Carter et al., 2015). After an uninsured household has experienced some adverse weather event, it usually either sell assets to achieve consumption smoothing and/or reduce expenditures on consumption for smoothing assets. This measure actually results in underestimation of income-generating capacity which can potentially push a farmer into the poverty trap.

As it was mentioned in the Section 2.2, basis risk can be also considered as one of the major challenges, which seem to increase the scepticism among farmers towards insurance companies and negatively affect demand for such relatively new insurance product as weather-index based one. Nevertheless, we would assume that there exist at least two possible solutions to the basis risk problem. First is that to minimize basis risk caused by the geographic issues: an extensive number of weather stations in a region is highly desirable. Although being costly this solution should also eliminate some data related issues. Second solution is to choose weather indexes that are related with the infrequent and highly covariate (affecting everyone) weather risks. Consequently, as those risks affect the majority of people in a region, individual losses are then more likely to be highly correlated with the insured weather event (International Fund for Agricultural Development (IFAD), 2010). The second suggested solution seems relatively time consuming as the process of weather indices screening should be accompanied by the results of an analysis of the specifics of a country, region, or area, then the chosen index should be checked for viability.

As payout and premium calculations are based on the weather records the product suggests greater transparency for the customers (World Bank, 2011). Although it is necessary for the insurer to clearly explain to farmers the mechanism how and when the payment is triggered, i.e., when we agreed that the WII offers greater transparency to farmers, we assumed that in the country where the insurance policy is be purchased, the problem of data scarcity is minimal. That is, in a country there is an opportunity for a farmer and insurer to request and access the data of interest (e.g., weather records, crop yields, price data). In those countries where data scarcity is still a challenge many studies are done to overcome it. Ntukamazina et al. (2017) provided an example about the software application – the Livelihoods, Early Assessment and Protection (LEAP) – developed in Ethiopia “which uses ground and satellite rainfall data to map the whole of Ethiopia with ability of covering areas without weather stations.”

Turning to risk management, many authors believe (e.g., International Fund of Agricultural Development (IFAD), 2011)) that if WII becomes a part of an integrated approach to risk management it has a great potential to support agricultural development. Insurance often cannot add value to a farmer’s livelihood unless his/her income can be enhanced through availability of other services. Insured farmers do not only get an opportunity to transfer the risk, but also get better access to agricultural information, modern technologies, credit and other financial services.

## 2.4 Policy Preliminary Assessments

It is important to understand that there is no one single way to form a weather index-based insurance product. On the one hand, efficiency of a contract is dependent on the combination of indexed variable (weather index), triggering measurement (trigger) for indexed variable, period covered by index, start of cover period, number of phases into which covered period is divided and payout option. On the other hand, diversified prior research needs to be established before starting the complicated product construction and intervention processes. "Establishment of index insurance product and identification of the fair premium demands three main steps: collecting long-term yield and weather index data; identifying the index value and payoffs for each year; and calculating an average payoff and discounting with the risk-free interest rate (e.g., Odening et al., 2007)" Bobojonov et al., (2014)). Extensive preliminary assessment should be undertaken. It allows to get an overview of conditions of a country/area generally related with the potential suitability of the WII product. Following the logics suggested by International Fund of Agricultural Development (IFAD) (2011), we would consider five key areas to examine before moving to the more technical part of the assessment for product creation:

- Country context: assessment of a rural development stage, political, demographic and socio-economic specifics, analyses of financial and agriculture sector features etc.;
- Weather: vulnerability profile, climate zone characteristics;
- Insurance: review of existing insurance companies and products;
- Demand: defining the extent of crop cultivation in a given area and its exposure to specific weather risk;
- ″Intermediaries: existing delivery channels, microfinance institutions, input suppliers, etc. "

Theoretically, these key areas require a great amount of information to be collected through the use of remotely accessed local data or through a desk review, then checked whether variety of pre-conditions applied to data is obtainable. No doubt, the situation where all conditions will be fulfilled and all required data will be available is too idealistic and is rare to happen in the real world. Therefore, it is another challenge for the insurance company to be able to identify which conditions are necessary and sufficient for further processing of WII product construction. World Bank (2011) stated that, if some of the necessary information is missing, alternative solutions and technology should be available for solving this issue of information scarcity. E.g., weather generators,[2] aimed to simulate some specific weather variable, can be used to fulfill missing values in the weather records.

In terms of this master's thesis, we decided to skip the detailed explanations about how all of the five key areas of preliminary assessment can be processed. Instead, we are going to briefly describe some insights derived from visual statistics, which are considered to be

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[2] "Weather generator (WG) produces synthetic time series of weather data of unlimited length for a location based on the statistical characteristics of observed weather at that location." Source: `https://www.ipcc-data.org/guidelines/pages/weather_generators.html`

relevant for the preliminary assessment.

Figure 1: Worldwide employment rate in agriculture, % of total employment Retrieved from `https://data.worldbank.org/indicator/sl.agr.empl.zs?end=2018&start=2018&view=map&year=2018` at April 24, 2019.

There are numerous visual examples that might be helpful to review, e.g., maps reflecting a rural development stage in different countries, weather conditions, poverty and education level within a population etc. Figure 1 describes the rate of employment in agriculture among different countries. Figure 1 shows that over 50% of the people are employed in agriculture within a large part of the African continent. More accurate geographically-based conclusions about employment in agriculture worldwide are as follows: more than 51.2% of people in west, east, central Africa and Afghanistan, Tajikistan, Nepal, Dem. People's Republic Korea; from 33.24 to 51.2% of people of Albania, Liberia, Cote d'Ivoire, Ghana, Togo, Nigeria, Gabon, Angola, Madagascar, Kenya, Yemen, Georgia, Azerbaijan, Pakistan, India, Myanmar, Vietnam; from 20.87 to 33.24% of people of Honduras, Nicaragua, Ecuador, Peru, Bolivia, Paraguay, Egypt, Romania, Syrian Arab Rep., Uzbekistan, Kyrgyz Rep., Mongolia, Thailand, Cambodia, Indonesia, Philippines. The USA, Russia and China, being the biggest countries by population and area, also "frequently appear as top producers" of the major vegetables and cereals (Simpson, S.D., 2012, July), showed relatively small percentage (somewhere below 9.35%) of citizens employed in agriculture.

For Figure 1 to be relevant for making an inference for an insurer, it needs to be considered together with a weather risk mapping created for a particular country or area. Risk mapping can be a helpful tool for reviewing a geographical picture of the level of risk due to different weather conditions. For this kind of risk assessment, it should be sufficient to rely on the information that already exists and synthesize it, so conducting new studies or analyzing raw data may not be of value. One of the possible ways to conduct a risk mapping is to construct an overlaying map of a country's (or a region's, an area's) weather risks, agro-ecological zones,[3] location of weather stations, location of farms and type of crop production, crop yield levels etc. If different problems within a chosen area exist their overlapping will appear on the map meaning that multi-peril insurance scheme should be more suitable (World Bank, 2011).

Figure 2 shows the world map of drought vulnerability "derived from an arithmetic composite model which combines social, economic and infrastructural factors computed with a non-compensatory aggregation schema of vulnerability indicators," (Carrão et al., 2016). This particular figure is an example of how one level of the risks map might look like. Unfortunately, Carrão et al. (2016) did not mention what index exactly was used to create the map depicted on Figure 2. There exist numerous indices developed to indicate the severity of different types of drought. For example, the Palmer Drought Severity Index, Percent of Normal Index, Standardize Precipitation Index, Crop Moisture Index, Surface Water Supply Index, and Reclamation Drought Index (FEMA, 1997). Islam and Ryan (2016) reason, "that a single weather variable cannot describe everything about the original data, and an index can only give an approximation of the real event."

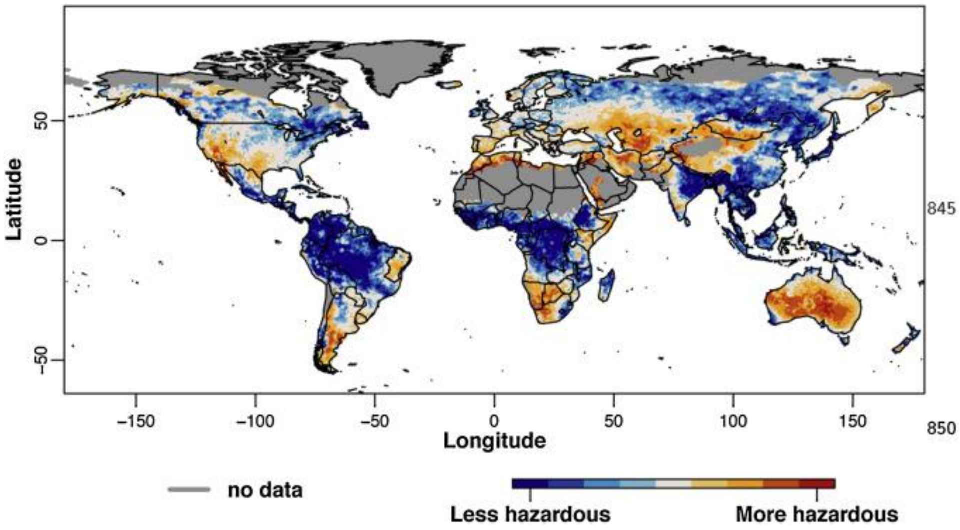

Figure 2: World map of drought hazard (Carrão et al., 2016). Retrieved at `https://ars.els-cdn.com/content/image/1-s2.0-S0959378016300565-gr3.jpg` at

According to this map Central America, North-West of South America, Cnetral, South and South-East Asia, and almost all Africa – with the exception of South Africa, are the most vulnerable regions to drought. However, it is notable that, as the model used

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[3] Agro-ecological zone (AEZ) - a land resource mapping unit, defined in terms of climate, landform and soils, and/or land cover, and having a specific range of potentials and constraints for land use. Source: `http://www.fao.org/3/W2962E/w2962e-03.htm`

by Carrão et al. (2016) takes into account social, economic and infrastructural factors, countries located in the same climatic zone show different vulnerability. If we take as an example tropical zone[4] (it covers Central South America, upper half of the South America (up until Brazil and Bolivia), almost all Africa, part of Western, South and South-East Asia, half of Australia) which is characterized by warm-to-hot and moist weather conditions, we may assume that some countries, due to the overall level of development, seem to be more successful in managing drought risk than others.

These results derived from visual inspection can become a basis for the more focused further assessment of the potential demand, insurance market's development stage, area's economic, political, financial and agricultural specifics. Although these pieces of information should be combined with the information describing: the state of an insurance industry formation (awareness about existing insurance products, accessibility of insurance products, availability of other risk management financial tools, delivery channels etc.); political, financial, demographic, socio-economic, agriculture sectors specifics; the specific crop species cultivated in the given area is required to assess crop vulnerability.

## 2.5 Policy Parameters

Designing weather index-based insurance products is extremely complex, in part due to the effort required to identify a weather index that is correlated with agricultural loss and thus minimizes basis risk. In some cases, simple indexes such as the average of daily average temperature (AAT) will be appropriate, while in other cases an actuary may need to create a unique mix of different weather indexes. All in all, the procedure of modelling an insurance contract which gives the protection against unfavorable weather events should start from defining of an index that accurately reflects the losses faced by clients. Consequently, the design of the index insurance products can vary a lot depending on the variable to be indexed, the object of the cover and various operating conditions.

As it was mentioned before there are a few parameters a mix of which have a critical influence on the nature of the agriculture insurance product to be offered. Different adverse weather characteristics can be transformed into the weather index, representing the risk to be insured. According to International Fund of Agricultural Development (IFAD) (2017), practitioners usually divide indexed variables into input-based and output-based. Rainfall-based indexes can be considered as an example of an input-based index. Insurance contract, e.g., against excessive rainfall, is designed assuming that the observed input is one of the essential conditions of the specific crop production.

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[4] Tropical zone (i.e., tropics) are areas of "climate radiation," which are limited by the Tropic of Cancer and the Tropic of Capricorn in the northern and southern latitudes. Source: `https://globalforestatlas.yale.edu/tropical-zone`

Output-based indexes focus on the output side, i.e., they are attempted to reflect the yield series and represented by, e.g., vegetation indices[5] or evapotranspiration[6]. An appropriate index will predict loss events and their magnitude with a sufficient level of accuracy. In some cases, simple indexes such as the amount of total cumulative rainfall will be appropriate, while in other cases much more complicated indexes are preferred.

To convert an index into an insurance design, it is necessary to set criteria regulating the provision of payouts (see, e.g., International Fund of Agricultural Development (IFAD), 2011, 2017):

- the weather index: generalized measure of underlying weather variable;
- maximum payout: the highest payout the contract can provide;
- trigger (or strike): a threshold for the weather index above or below which payouts are due;
- exit (or limit): the threshold for the weather index above or below which no (additional incremental) payout will be applied;
- tick (or conversion factor): the payout value per unit deviation from the trigger;
- period of coverage (insured period): dynamical or fixed duration period over which the payouts are provided
- distance between the insured area (region, territory, rayon) and the reference weather station.
- others

Usually payouts are calculated with incorporation of the trigger(s), which are tracked in a particular zone by so called reference station throughout the insured period. There are also a few different ways to determine the trigger value. The measure of the observed variable can be maximum or minimum value to be reached in order to generate a payout (e.g. highest/lowest temperature); an average over a period of time (e.g. average temperature); cumulative (e.g. sum of mm of rainfall over a defined period).

The coverage period, defined in a contract, can cover specific periods according to the crop's exposure to different risks during its life stages (e.g. flowering, maturity) or the entire crop calendar from sowing to harvest. To describe the dates covered by the

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[5] Vegetation index is a mathematical combination or transformation of spectral bands that accentuates the spectral properties of green plants so that they appear distinct from other image features. Retrieved from: `http://web.pdx.edu/~nauna/resources/8-2012_lecture1-vegetationindicies.pdf`.

[6] The Standardized Precipitation Evapotranspiration Index (SPEI) is designed to take into account both precipitation and potential evapotranspiration (PET) in determining drought. Retrieved from: `https://climatedataguide.ucar.edu/climate-data/standardized-precipitation-evapotranspiration-index-spe`

insurance contract, the index-insurance uses the term contract window (index window). The possibility of developing a “dynamic start” of the crop season is of particular relevance for the farmers operating in areas where “the start of certain agricultural activities and planting is strictly linked to the occurrence of determined environmental conditions”, International Fund of Agricultural Development (IFAD) (2017).

## 2.6 Policy Payout Structure

According to International Fund for Agricultural Development (IFAD) (2010), “all buyers in the same region are offered the same contract terms per monetary unit of insurance coverage”. That is, they pay the same rate of premium and, once an event has triggered payouts, receive the same rate of payout; their total payout depends on the value of the insurance coverage purchased. However, the actual sum received by an insured party is dependent on the quantity of units of insured area.

The payout structure triggered by the index can be “incremental,” i.e., the damage is considered to be progressively more severe as the deviation from the trigger increases or it can provide a “fixed sum” payment “in case if all-or-nothing type of event is covered, such as cases in which reaching a particularly sensitive threshold (e.g. a critical temperature) generates a total loss”, International Fund of Agricultural Development (IFAD) (2017). Maximum payout in the WII product should be set in accordance with recommendations of an agricultural results assessment specialist, because its size has to be sufficient for an insured farmer to be able to cover his losses of a crop yield caused by particular weather condition, described by the WI. Jewson and Brix (2005) stated, that, within the concept of the weather derivatives “Any function could be used as a pay-off function, but in practice only a small number of simple structures, with straightforward economic purposes, are common.” The most “commonly used forms of weather derivatives” correspond to the call, put or swap payoff functions (Zeng, 2000). Call payoff function describes the situation, when the weather index is bigger than the threshold level prescribed for this index; put payoff function describes the situation, when the weather index is lower than the threshold level prescribed for this index. Within the concept of WII claim sizes are constructed, similarly to weather derivatives, incorporating call and put payoff function designs. However, according to Zeng (2000), a buyer of the weather derivative contract will receive a payment, if it occurred, at the end of the contract, but the concept of WII implies that a farmer can receive a payout once the specific weather event occurs, such as unfavorable rainfall level, adverse temperature regimes, excessive snowfalls, flood, hail.

To create a visual example of the “incremental” type of a payout’s structure we have analyzed some information available in the internet and also made conclusions according to the Figure 1., and Figure 2. First, as it was presented on the Figure 1, about 30%

of Syria's population is employed in agriculture resulting in a great dependence of the country prosperity on yields and production results. In addition, the sector accounts for an estimated 26% of Syria's gross domestic product (Food and Agriculture Organization of the United Nations, 2017). Second, according to the Figure 2, the country's agricultural areas are highly vulnerable to drought, which means that various weather variables such as temperature, precipitation level, evapotranspiration level can be used for constructing the WI, calculation of a tick size, defining the construction of a claim size design. We will proceed with data describing average monthly level of rainfall in millimeters collected for the years 1991–2015.

Whether Syria is exposed to high temperatures and water resources usage is an issue, "sufficient rainfall supports cultivation in an arc from the southwest, near the border with Israel and Lebanon, extending northward to the Turkish border and eastward along that border to Iraq", International Business Publications, USA (2015). However, according to the same source, the rain-fed farming is still risky "because the amount of rainfall and its timing varies considerably from year to year", thus, sequential dry years are not rare.

In terms of this hypothetical example of the WII product's payout structure, I decided to consider wheat crop production specifically. The main reason explaining this choice is that area of the land planted with wheat amounts to 61% of the whole assessed lands of wheat farmers according to the data of 2016 (Assistance coordination unit Syrian food Security program (Qamh)., 2016). To set the trigger value we relied on the founding of Aw-Hassan et al., (2014): "to harvest 6.6 t/ha of durum wheat grain, a farmer had to irrigate at a rate of 4500–5100 m3/ha (510 mm) if 250 mm of rainfall (or 2500 m3/ha) was received". Taking all mentioned above into account we took the value of approximately 42 mm/month as a trigger. For monetary units we shall use the currency of Syria, the Syrian Pound (SYP). According to the Figure 3, one can conclude that: the maximum payout is set at SYP610 provided for rainfall levels of 25 mm/month or below; any time the average monthly precipitation falls below 42 mm/month claims are paid.

One specific feature makes weather index-based products construction even more challenging in comparison with traditional indemnity-based contracts. Adhering the classic approach to a contract pricing the insurer constitute rules and conditions based mainly on probabilistic models, and, usually, payouts are made in accordance to an ex-post loss assessment. For weather index-based products, however, it is necessary to agree to an ex-ante payout scale that will determine how much the contract will pay for each unit of weather variable. Tick size is aimed to express the monetary value of each unit of the WI deviation from the trigger. International Fund of Agricultural Development (IFAD) (2017) provided the following formula for calculating a tick size:

$$\text{Tick} = \frac{\text{Maximum payout}}{\text{Trigger-Exit}}. \tag{1}$$

However, Matsuda (2013), describing two different weather index insurance products

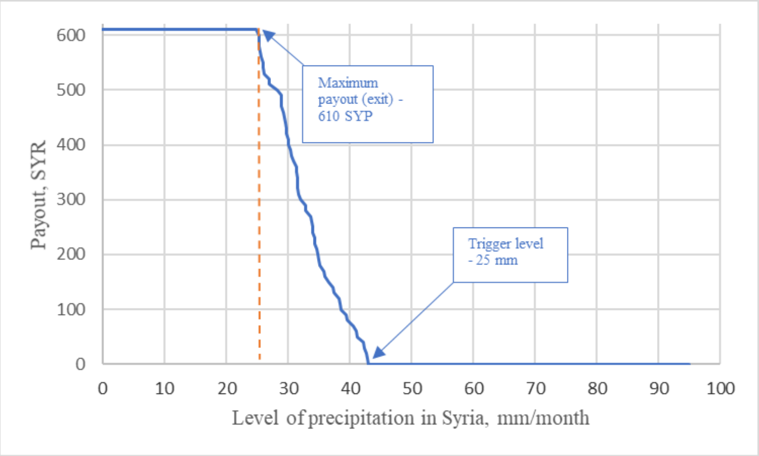

Figure 3: Example of payout structure for a hypothetical insurance against the deficit of precipitation.

which were sold in India, noted that the tick size can be a fixed sum. Therefore, an insurer can keep the right to define a payout structure and its parameters in various ways for different weather indexes, taking into account the insurable crop's features, particular country's socio-economic, socio-demographic, financial specifics etc.

## Examples of Policies

Matsuda (2013) explains two real-life examples of WII type of insurance product provided in India, the rainfall index insurance and temperature index insurance, sold by one of the major insurance companies in India. All monetary values in this examples are given in Indian Rupees, denoted by Rs. Rainfall index insurance type of a contract, called BBY, was developed to cover losses not only from the total rainfall, but from the excess rain and consecutive dryness. Insurance provider specified the premium per acre to be Rs 750, and sum insured to be Rs 9 000, giving the approximate premium rate at the level of 8.3%. In turn, farmers were asked to state the number of acres to be insured.

In the contract there were four phases specified and each of them has its own strikes and notionals (in these particular designs, notional has the same meaning as the monetary value per unit of deviation of the WI from trigger). Precipitation level is denoted by $r$ (mm), lower and upper bounds of two strike ranges by $(U_1, L_1)$ and $(U_2, L_2)$ with $(U_1 > L_1 = U_2 > L_2)$ accordingly and notionals for each range of strike by $N_1$ and $N_2$. Then, claim payout (Rs per acre) on rainfall deficiency is calculated as follows:

$$\text{Per Acre Claim Payout} = \begin{cases} N_1\,(U_1 - r) & \text{if } L_1 < r < U_1 \\ N_1\,(U_1 - L_1) + N_2\,(U_2 - r) & \text{if } L_2 < r < U_2. \end{cases} \quad (2)$$

Table 1: MBY Contract Schema

| | Phase I | | Phase II | | | |
|---|---|---|---|---|---|---|
| | Period 1<br>$\tau_1 - \tau_2$ | Period 2<br>$\tau_3 - \tau_4$ | Period 1<br>$\tau_5 - \tau_6$ | Period 2<br>$\tau_7 - \tau_8$ | Period 3<br>$\tau_9 - \tau_{10}$ | Period 4<br>$\tau_{11} - \tau_{12}$ |
| Trigger (℃) | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ | $T_6$ |
| Strike (℃) | $S_{\text{Phase 1}}$ | | $S_{\text{Phase 2}}$ | | | |
| Exit (℃) | $E_{\text{Phase 1}}$ | | $E_{\text{Phase 2}}$ | | | |
| Notional (Rs) | $N_{\text{Phase 1}}$ | | $N_{\text{Phase 1}}$ | | | |

Note: The index of Phase I is the two-week average of the daily maximum temperature.
The index of Phase II is the two-week average of the daily average temperature.

Matsuda (2013) stated “A claim for excess rainfall is paid when the cumulative rainfall of any two consecutive days in a phase is more than the strike.” The formula needed for the claim calculation is as follows:

$$\text{Per Acre Claim Payout} = \max\{\text{CR2CD} - \text{Strike})\text{Notional}, 0\} \tag{3}$$

where CR2CD denotes the cumulative rainfall of any two consecutive days. The Consecutive Dry Days (CDD) index was based on the weather data collected between July 5 to September 15. When the total number of consecutive days with a daily rainfall level of less than 2.5 mm exceeded a strike, payout was made. The total claim payout of BBY 2012 is the sum of the payouts for all three covers.

Another example is about the temperature-based insurance product called Mausam Bima Yojna (MBY). MBY is a unique index insurance product that insures against damage of crops exposed to extreme heat during the growing and flowering periods. Within the framework of MBY the insurance provider specified the premium per acre to be Rs 560, and sum insured to be Rs 7 000, giving the premium rate at the level of 8%. The contract’s design is summarized in Table 1. Two phases and six periods each lasts two weeks are pre-defined in terms of this insurance product. Triggers, strikes and exits are different for each phase.

To calculate the claim payout of Phase I, suppose that the actual temperatures observed during Period 1 and Period 2 were $X_1$(℃) and $X_2$ (℃). Triggers, $T_1$ (℃) and $T_2$ (℃), represent the average of the daily average temperature (DAT) and the average of the daily maximum temperature for each two-week period respectively. The strike and exit for each period are defined as $S_{\text{Phase 1}}$ (℃) and $E_{\text{Phase 1}}$ (℃), respectively. Then, the claim payout (Rs) is calculated as follows:

$$\begin{aligned}&\text{Per Acre Claim Payout}\\&\quad = N_{\text{Phase 1}} \min\{\max\{(X_1 - T_1) + (X_2 - T_2) - S_{\text{Phase 1}}, 0\}, (E_{\text{Phase 1}} - S_{\text{Phase 1}})\}\end{aligned} \tag{4}$$

After the coverage period, the insurance provider declares the amount of the claim on the basis of the weather data reported by the Indian Meteorological Department. If there are positive claim payouts, an insurance agent visits the village to distribute checks to the individual clients before the beginning of the next season (Matsuda, 2013).

## 2.7 Policy Pricing

There are different methods applied for insurance contract pricing but generally the insurance premium for different types of a contract will consist of the expected loss, risk loading or risk margin "that corresponds to a capital reserve charge required to underwrite the risk at a target level for the business" World Bank (2011), and administrative costs. Therefore, the formula for a premium calculation can be presented as follows:

$$\text{Premium} = \text{Expected Loss} + \text{Risk Margin} + \text{Administrative Costs}. \qquad (5)$$

Expected loss is the expected size of incurred claims. The risk margin's aim is to smooth an insurer's excessive payouts when extreme events happen so that the risk taken for this uncertainty will be compensated. While constructing a WII product, an actuary should establish the values of the expected loss and the risk margin from historical weather data. As the weather data collected within some specific region may have missing values or hide trends, defined values of risk margin and expected loss may include an adjustment to compensate for uncertainties.

In this thesis we focus on evaluating the expected loss in (4) while the risk margin and administrative costs stay out of our scope. For the valuation of the expected loss of the weather index-based insurance several methods available (see, e.g., Jewson and Brix, Ch. 3- Ch. 6), for example the historical (Burn) approach or the index modelling approach. Under the **burn approach**,the expected claim-to-be-paid size is computed by using the mean value of the historical payouts. On the one hand, this method is quick and simple. On the other hand, due to simplicity, it is not possible to incorporate numerous statistical and physical characteristics of the particular regional or area weather system. So, the method can serve only as a rough guideline, rather than the accurate baseline. However, for WII historical data is often not available. Che Tiab and Benth (2012) suggested to create a hypothetical data based on policy design and historical weather data available. Under **index modelling**, the claim size is constructed by incorporation of the weather index. This method suggests two options: 1) provide a model for the underlying weather index; 2) find and fit distribution for payoff or index. An example of using all mentioned valuation options is provided in Che Tiab and Benth (2012). Although, Jewson and Brix (2005) declared, that for pricing weather derivatives: "Modelling the index distribution is slightly preferable because the index distribution has smooth tails". Developing a (time-serie) model for the underlying weather index focuses on modelling the historical weather index outcomes by using common statistical time series models (i.e. ARMA). Whereas historical payouts, within index modelling method, are modelled by finding an appropriate parametric or non-parametric distribution. After the distribution was fitted to the historical payouts or model for the weather index was found one can compute the expected pay-off, the distribution of the financial outcomes of the contract and so on.

# 3 Designing Temperature Index Insurances

We consider a farmer, who wishes to protect his crops for adverse temperature events during some period. To become a WII contract holder the farmer should buy it prior to the beginning of a specified insured period. In this thesis we aim to provide daily average temperature (DAT) based insurance for winter wheat production in Tartu County. First we provide ideas for designing payout functions against unfavourable temperature. For pricing we will follow Che Tiab and Benth (2012): based on historical temperature data we create the corresponding hypothetical payout (claims) for various policy designs. For hypothetical payout we apply historical (burn) analysis and modelling via distributions supported on semi-infinite $[0,\infty)$ interval: exponential,Weibull, log-normal, gamma, log-logistic, Pareto.

In our design we follow the average of (daily) average temperature (AAT) index provided by Jewson and Brix (2005), and modification of the design provided Che Tiab and Benth (2012). The design of policy is inspired by winter wheat production and its dependence on the temperature regime. For our modeling we used data collected by Tartu Tõravere meteoroloogiajaam and describing daily average temperature during 1988-2019 in Tartu county.

For the temperature insurance contract to be attractive for a client, the insurer must create unique mix of a contract parameters: indexed variable, triggering measurement for the index, period covered, start of coverage period, number of phases covered and payout structure etc. This mix can vary according to the country/region/area specifics, features of a crop insured. In general, an actuary can combine many different measurements, based on which claim size design will be constructed. In this thesis we consider 3 structures of a payout design: monthly average of daily average temperatures (ADAT), daily average temperature (DAT), changes in daily average temperature fluctuations (CDAT). WII contract based on ADAT index and DATs is assumed to cover losses in the winter wheat yield caused by cold, whereas contract based on CDAT index will hedge against temperature fluctuations.

## 3.1 Daily Average Temperature in 1988-2018 in Tartu County

Meteorological data about the daily average temperature (DAT) during 1988-2019 time period collected by Tartu Tõravere meteoroloogiajaam was kindly provided by Riigi Ilmateenistus. Notable, the approach for defining DAT can vary from country to country. Winter wheat yield data in 1988-2018 was is publicly available by Statistics Estonia (2019). All calculations are done by MC Excel (Microsoft, 2019) and R software (The R Project for Statistical Computing, 2019) Before conducting any analysis, as Che Tiab and Benth (2012) suggested, all measurements on February 29 were removed to synchronize the length of the years to 365 days. In total, 11 399 records covering 31 year of DATs were observed.

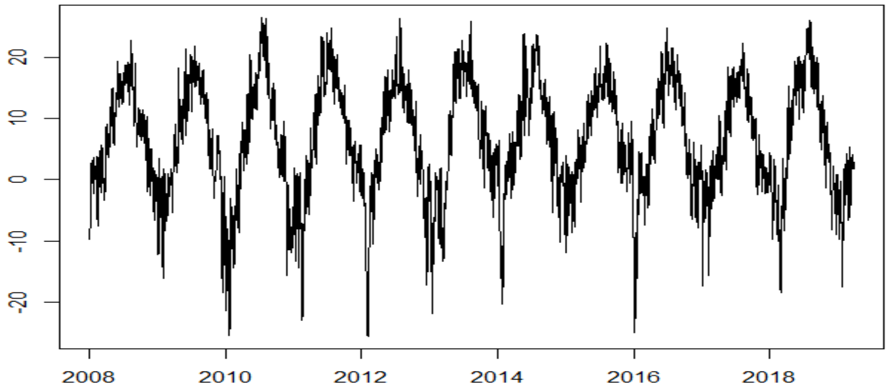

Figure 4: Daily average temperatures (DAT) measured at the Tõravere station (Tartu county, Estonia) during the period of 01.01.1988 – 25.03.2019.

To make the representation of the DATs time series more convenient for the overview, Figure 4., plots the temperatures recorded between 01\01\2008 and 25\03\2019. Strong seasonality with the duration of 1 year is observed, the lowest and highest temperatures were recorded at the level of -27.3°C and 27.1°C accordingly, with the mean being equal to 6.7°C. The histogram of DATs in Tartu county during the whole time period considered for this study is presented in the Figure 5. The skewness coefficient is -0.29259, indicating that the average daily temperatures' distribution is skewed towards left. The negative excess kurtosis (-0.37175) indicates a light-tailed data distribution. By R function `ad.test` Anderson-Darling test for the composite hypothesis of normality of DATs was performed and resulted in rejection of the null hypothesis at significance level of 5%, i.e., there is very small probability that on Figure 5, we see normally distributed data.

Following the temperature patterns reflected by the Figure 5. we can conclude that in the

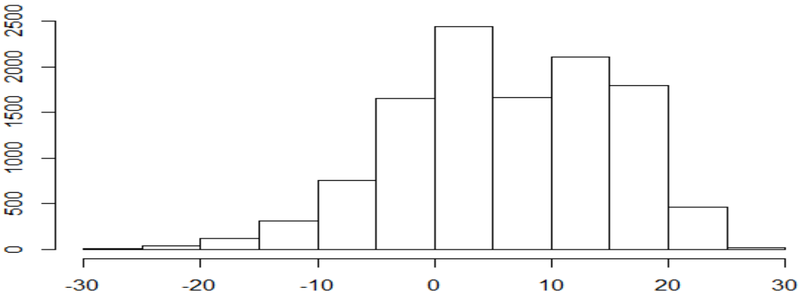

Figure 5: Daily average temperatures (DAT) measured at the Tõravere station (Tartu county, Estonia) county during of 01.01.2008 – 25.03.2019.

Tartu county the number of days when DAT was above 0°C significantly exceeds those days where DAT was below 0°C.

## 3.2 Winter Wheat Characteristics

To be more precise, in determining the parameters of the insurance contract, the combination of which directly affects its price, we decided to take into account some characteristics of a winter wheat and explore the influence of a temperature regime on this crop. Graphs for winter wheat yield and DAT are given in Annex A.

The importance of the study is confirmed by the fact that approximately 690 208 hectares of the farmed agricultural area of Estonia (2016) was dedicated to arable crop production and over half of this area (53%) was cultivated for cereal production, whereas wheat counted 47% in the structure of cereals growing in 2016 (Ministry of Rural Affairs of the Republic of Estonia, 2017).

In this thesis the temperature data was gathered from Tõravere station, Tartu county. In 2001 Tartu county was the second region by the number of agricultural holdings and the first one by the size of sown area devoted to the winter wheat (Statistics Estonia, 2019). In general, the size of utilized agricultural area[7] in Estonia showed positive dynamics by increasing its size from 945 922 (ha) in 2011 to 1 003 505 (ha) in 2016. Following the numbers from the Table 2., concluded that winter wheat production outperforms other crops' production by three measurements: growing area, harvest and yield.

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[7] Utilized agricultural area (UAA) - the total area taken up by arable land, permanent grassland, permanent crops and kitchen gardens used by the holding, regardless of the type of tenure or of whether it is used as a part of common land. Source:`https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Utilised_agricultural_area_%28UAA%29`

Table 2: Crop production in Estonia during the period of 2014 - 2016 (Ministry of Rural Affairs of the Republic of Estonia, 2017).

| Crop | 2014 | | | 2015 | | | 2016 | | |
|---|---|---|---|---|---|---|---|---|---|
| | growing area (th ha) | harvest (th tons) | yield (kg/ ha) | growing area (th ha) | harvest (th tons) | yield (kg/ ha) | growing area (th ha) | harvest (th tons) | yield (kg/ ha) |
| **Total cereals, incl.** | 332.9 | 1 221.6 | 3 669 | 350.4 | 1 535 | 4 382 | 351.4 | 934.1 | 2 658 |
| rye | 15.4 | 49.6 | 3 211 | 14.3 | 54.7 | 3 823 | 12.4 | 32.4 | 2 616 |
| winter wheat | 81.0 | 347.8 | 4 295 | 97.8 | 518.5 | 5 302 | 90.7 | 259.1 | 2 857 |
| spring wheat | 73.4 | 267.7 | 3 648 | 71.9 | 294.1 | 4 090 | 73.8 | 196.4 | 2 660 |
| spring barley | 125.6 | 457.5 | 3 641 | 130.3 | 551.5 | 4 232 | 133.6 | 352.6 | 2 639 |
| oats | 27.3 | 65 | 2 384 | 24.4 | 67.8 | 2 781 | 29.3 | 64.5 | 2 201 |

Although the statistic presented in Table 2., is aimed to give better understanding about the character of crop production in Estonia, our further investigation of winter wheat's characteristics is more general. The main reason for this generalization is that we do not ascertain information, regarding the species of winter wheat specifically cultivated in Tartu, Estonia. Therefore, in practice, an insurer should get an explicit statistic about a sample of households which might have been interested in acquisition of WII product, including the species of crops cultivated, historical estimated yields etc.

Returning to the concept of WII, specially developed to cover the losses that farmers may incur due to unfavorable weather conditions, we would like to say, that to investigate the reliability of the pre-defined weather index, insurer needs to take into account some specific features of the crop. It is essential to understand at what stage of cultivation and\or during what period of a year, winter wheat is more exposed to the negative impact of the weather conditions: excessive rains, low\high temperatures, temperature fluctuations, shortage in daily sunlight hours etc. Furthermore, to be able to assess the feasibility of embarking upon WII product pilot, which will insure winter wheat producers, an insurer needs to construct a viable size claim design, and, consequently calculate the premium size.

The sowing period for winter wheat usually starts in September, but harvesting takes place in the second half of August (Pike and Robards, 2017). "During the calendar winter (Dec.22 to Mar. 20), prolonged periods of cold weather increase the potential for low temperature damage to winter wheat," - Fowler (2018). Winter wheat's seedlings (being one of the most cold-resistant) can tolerate short periods of low temperatures, e.g., Pike and Robards (2017) found that “50 hours exposure to -18°C in controlled environment rooms reduces the minimum survival temperature of Norstar winter wheat from -24 to -18°C”. According to Estonian Rural Development Foundation Advisory Service (2019) “Winter wheat is less coldproof than winter rye. They survive/tolerate -20°C to 25°C.

Another finding of Pike and Robards (2017) is about the influence of the variability of the temperature regime, i.e., the specific of winter wheat crop is such that when temperatures fall subtly, the crop develops its winter hardiness. So, the potential crop damage can occur if “an extended period of favorable temperatures is followed by a rapid onset of very cold weather.” Thus, an insurance specialist should take into account that not only temperatures below the survival range can harm the winter wheat, but also the duration of exposure to the potentially harmful temperatures and the severity of temperature drops.

In Table 3 we presented those weather events, which we consider to be potentially harmful for the winter wheat seedings, according to the above-mentioned characteristics of the crop.

Table 3: Weather events unfavorably affecting winter wheat seeding

| | December | January | February |
|---|---|---|---|
| Minimum DAT | -25.8°C | -27.3°C | -25.6°C |
| Nr of days DAT $< -20°C$ | 5 | 21 | 22 |
| Number of cases of more than 2 days exposure to the $< -20°C$ | 1 | 5 | 6 |

Fowler and Greer (2003) found, that the process of cold acclimation of the winter wheat “can be stopped, reversed, and restarted”, i.e., winter hardiness of the crop can be decreased or lost if “acclimated winter cereals are exposed to warm crown temperatures that promote active plant growth.”

## 3.3 Monthly ADAT Index Based Policy

As the first possible option for designing claim sizes for pricing the weather index insurance product, we considered to use an average of average temperature (AAT) index. According to Jewson and Brix (2005), pp. 16, this index is considered to be more intuitive measure of a temperature variability. Although, we suggest to keep in mind that this index and its usage for pricing is mainly applicable in the concept of weather derivatives, which means that it may not lead to the accurate and viable results when we implement this concept for an insurance product pricing.

Average of average temperature index is introduced in Jewson and Brix (2005), pp. 16. It is based on the average of average of some time interval, called smoothing period (e.g., a week, a month). Let $\tau_1$ denote the start of smoothing period, and $\tau_2$ the end, then the average of daily average temperature (ADAT) for a smoothing period is $\mathrm{ADAT}(\tau_1, \tau_2) =$ ADAT,

$$\mathrm{ADAT}(\tau_1, \tau_2) = \frac{1}{N} \sum_{j=1}^{N} \mathrm{DAT}, \tag{6}$$

where $N = \tau_2 - \tau_1$. The period from $\tau_1$ to $\tau_2$ is called smoothing period (e.g., a week, a month, etc). In this thesis we choose smoothing period one month. As we were intended to investigate the influence of temperatures below 0°C on the crop performance we are interested in those months, where low temperatures were recorded (except April): October, November, December, January, February and March. Formula (7) demonstrates the calculation of the monthly ADAT index, that is the monthly average of DAT, denoted by $ADAT_{i,k}$ for a month $i$ in a year $k$,

$$\mathrm{ADAT}_{i,k}(\tau_{1i}, \tau_{2i}) = \frac{1}{N_i} \sum_{j=1}^{N_i} \mathrm{DAT}_j \tag{7}$$

where $i$ denotes the month, $k$ denotes the year, Ni $N_i = \tau_{2i} -, \tau_{1i}$ corresponds to the duration of the $i$-th insured month (for each $i$ we consider that $\tau_{1i}$ denotes the beginning of a month, $\tau_{2i}$ the end of a month), and $\mathrm{DAT}_j$ is the daily average temperature of day $j$ (within the month $i$). Therefore, for these particular definitions of the ADAT index ($N_i$) varies from 31 to 28 days accordingly.

### 3.3.1 Payout Design and Parameters

For winter wheat in particular for Tartu county we design insurance policy with the period of coverage from October 01 to March 31. We set the policy payout as follows,

$$X_{i,k}(\tau_{1i,k}, \tau_{2i,k}) = h_i N_i \max(E_i - \mathrm{ADAT}_{i,k}), 0) \tag{8}$$

where $E_i$ is the trigger for particular month $i$ (same for year $k$, $E_{i,k} = E_i$), $h_i$ is the monetary value for a period $i$ transforming $\max(E_i - \mathrm{ADAT}_{i,k}, 0)$, measured in degrees, into amount of money[8] (for same months we use same tick over years, that is, $h_{i,k} = h_i$). The value $h_i$ is called the tick value. The claim $X_{i,k}(\tau_{1i,k}, \tau_{2i,k})$ corresponds to 1 unit of an insured area (farmland, field). Usually the size of agricultural area is measured in hectares (ha), therefore we will consider that claim size is measured in monetary unit per 1 hectare. Note that in this thesis we calculate the hypothetical monthly payouts (claims), denoted by $X_{i,k}(\tau_{1i,k}, \tau_{2i,k}) = X_{i,k}$, fixed at the end of month $i$ (at time $\tau_{2i,k}$), from 1988 to 2018(19) (over $k = 1, ..., 31$ years) (see Section 4.1)

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[8] Currently we do not consider any inflation. We assume $h_i$ is normalized monthly amount per field unit over the considered years.

As ADAT index calculation is based on the smoothing of daily average temperatures for a given period and, therefore, it insures the cases when the average of average daily temperature falls below the trigger temperature.

This particular structure of the claim size implies that if the monthly average of daily average temperatures falls below some pre-defined for the $i$-th month trigger $(E_i)$ it may lead to the losses in a crop yield due to temperature falling. That immediately should trigger the payment. Note, that if the trigger value corresponds to monthly ADAT then it corresponds to daily payout of size $X_{i,k}/N_i$ (for 1 unit (ha) of field).

In our policy design the period of coverage includes 6 months numbered as follows: October is numbered as 1, November - 2, December - 3, January - 4, February - 5, March - 6. Based on that we construct two datasets over 1988-2019:

- monthly claims are constructed as

$$X_{i,k}, \quad i = 1, ..., 6, \tag{9}$$

  Obviously, $X_{i,k} = 0$ means no claim occurred.

- based on monthly claims we find annual (i.e., policy year based) claims,

$$X_k = \sum_{i=1}^{3} X_{i,k-1} + \sum_{i=4}^{6} X_{i,k}, \tag{10}$$

Note that in this thesis we calculate the hypothetical monthly payouts (claims), denoted by $X_{i,k}(\tau_{1i,k}, \tau_{2i,k}) = X_{i,k}$, from 1988 to 2019 (over $k = 1, ..., 31$ years) (see Section 4.2).

### 3.3.2 Viability of the ADAT indexes

As it was mentioned in the Section 2, in order to assess the performance of the weather index in terms of assessing yield, common method of checking is linear or quantile regression model between the index and historical crop yield data can be implemented. Notable, that having the yield measured in 1988 would mean that the crop was sowed in September of 1987 and harvested in August of 1988. The efficiency of the index can be established based on the degree to which they demonstrate the co-movements in their dynamics within a given historical period (World Bank, 2011). In the Annex A we provided the results of this visual assessment of the index's performance in terms of assessing the winter wheat yield.

However, as the AAT indexes for different months were not tested for stationarity assumption, as well as yearly yields, we can't measure correlation coefficient mathematically, because it would be necessary that both time series were stationary.

Even though, relying on the visual inspection of Fig.A.1.- Fig.A.6, we can see that yearly yield time series demonstrate increasing trend, while AAT index time series in each month demonstrate different patterns: in January there is identifiable descending trend, in February, March and October it is hard to verify if there are meaningful trends, in November and December there might be ascending trends. Although this graphs should be mainly considered as an illustrative tool. Nevertheless, e.g., in January changes in AATs were usually followed by changes, of the same directions, in yearly yields; in February changes of AATs usually were sharper than those in yearly yields, whereas they also seem to demonstrate co-movements in some years; dynamics of AATs in March showed verifiably similar patterns with dynamics of yearly yields since 2006; in December AATs and yearly yields demonstrated verifiable co-movements since 2000.

Although implementing this index for pricing WII product, which is aimed to insure against winter wheat yield losses due to the sharp temperature falls, may lead to the unrealistic results of historical and index modelling methods. We would suggest to explain it by saying, that using the average of daily average temperatures during a particular month gives even more smoothed sample of indexes which are the main determinants of the claim size. It implies that even if potentially harmful temperatures for the winter wheat, which, however, depend a lot on the species, were recorded, the resultant average value would be influenced by the quantity of days with "extremely" low temperatures. Consequently, there may be cases, when the winter wheat was exposed to the harmful temperatures and yield losses actually occurred, but if AAT index does not fall below the trigger value, farmer will not receive any payment. Furthermore, the definition of triggers will become more intuitive than scientifically sound, the same applies to the determination of the maximum payout for such WII product.

## 3.4 Daily CDAT Index Based Policy

The second option for designing a claim size is considered to be in a way that in case if there is a temperature change, which is defined as a difference between the $5^{th}$ and the $1^{st}$ DATs, greater than the trigger level $(E)$. We denote corresponding daily index by CDAT. The coverage of potential losses due to this change will be provided to the insured farmer(s) on a day $i$. Differently from ADAT design, here the index is valued daily, not as an (monthly) average. There is no smoothing period. The daily claims for this policy are denoted by $\text{CDAT}_{i,k}$ where $i$ is for the $i$th day (in the policy period $(\tau_{1,k}, \tau_{2,k})$) of $k$th year. As we were intended to investigate the influence of temperatures below 0°C on the crop performance we chose those months, where temperatures drops may occur: October, November, December, January, February, March, April. That is we assume, the length of period of coverage is around 211 days. In this particular design the payouts can be made daily, weekly, monthly or at the end of period of coverage. Note that differently from

ADAT index we fix same daily trigger for each day over 7 months period.

### 3.4.1 Policy Design and Parameters

For winter wheat in particular for Tartu county we design insurance policy with the period of coverage from December 01 to February 26(28). Daily claims corresponding to daily $\mathrm{DAT}_{i,k}$ we denote by $X_{i,k}$ where $i$ corresponds to day and $k$ corresponds to year. The claim size is defined as follows,

$$X_{i,k}(\tau_{1,k},\tau_{2,k}) = h_i \mathrm{abs}(\min(\mathrm{CDAT}_{i,k} - E, 0) =, \quad i \in (\tau_{1,k},\tau_{2,k}), \tag{11}$$

where $CDAT_{i,k} = DAT_i - DAT_{i-4}$, $h_i$ is daily tick value corresponding to the claims. Obviously, $X_{i,k} = 0$ means no claim occurred. Hereby, summing the daily claims, $X_{i,k},$ of $k$th year, over the period of coverage, $(\tau_{1,k},\tau_{2,k})$, the annual claims per year $k$ are found as follows

$$X_k = \sum_{i=\tau_{1,k}}^{\tau_{2,k}} X_{i,k}, \tag{12}$$

Note that in this thesis we calculate the hypothetical daily payouts (claims), denoted by $X_{i,k}(\tau_{1i,k},\tau_{2i,k}) = X_{i,k}$, from 1988 to 2019 (over $k = 1,...,31$ years) (see Section 4.2).

### 3.4.2 Viability of the CDAT index

Although previously we suggested to plot simple graph of correlation between an index and the yield, to assess the viability of CDAT for constructing various claim designs, in case of daily data usage this visual representation of their co-movements would be rather uninformative. The main reason behind this issue is that yield evaluation happens once a year. Therefore, using yearly dynamics of one variable of interest (yield) and daily data reflecting the changes in another variable (CDAT) will not give an insurer any better understanding about the character of their co-movements.

In the Section 3.2., regarding the specific features of winter wheat crop, we mentioned, that the crop might be injured due to low temperatures (whether there is a single day of an extreme cold, or more than 2 days exposure to the temperatures that might be lower than survival temperatures) and variability of temperature regime, i.e., when temperature changes too sharply (this change can be harmful if there has been a long period of favorable temperatures before it). Therefore, we consider, that the variability of temperature can be measured by CDAT index. However, in real life, implementation of the same size of difference between DATs on each insured period (e.g., the same CDAT for each month) can be too unrealistic, due to the different weather conditions which, usually, change quite significantly from month to month. Therefore, to construct the payoff design properly, based on CDAT index, it becomes highly important for an actuary to take into consideration facts (collected via questionnaire of farmers, derived in partnership with agricultural funds, scientific laboratories etc.) about what scale of variability of daily average temperatures and its "unexpectedness" should take place to become a hazard for the winter wheat yield.

Although, we would like to highlight, that CDAT index is experimental and was constructed by us, mainly, relying on assumptions about the potential "causation type" of relations between daily average temperature variability and the losses in winter wheat yields. There are several WI which was developed for pricing weather derivative products (and, thus, WII products too), e.g., Heat Growing Degree Days (HGDD), Chilling Growing Degree Days (CGDD) etc. (Zhang et al., 2017).

## 3.5 Daily DAT Index Based Policy

The third option for designing a claim size is aimed to insure against low temperatures, i.e., if DAT on a particular day falls below the trigger level $E$ the claim size will become positive and the payout will be calculated for a day $i$. Differently from ADAT design, here the index is daily value, not an (monthly) average. The daily claims for this policy are denoted by $\text{DAT}_{i,k}$ where $i$ is for the $i$th day (in the policy period from $\tau_{1,k},\tau_{2,k}$)) of $k$th year. As we were intended to investigate the influence of temperatures below 0°C on the crop performance we chose those months, where very low temperatures may occur: December, January, February. That is we assume, the length of period of coverage is around 90 days. In this particular design the payouts can be made daily, weekly, monthly or at the end of period of coverage. Note that differently from ADAT index we fix same daily trigger for each day over 3 months period.

### 3.5.1 Policy Design and Parameters

For winter wheat in particular for Tartu county we design insurance policy with the period of coverage from October 01 to April 31. Daily claims corresponding to daily $\text{CDAT}_{i,k}$ we denote by $X_{i,k}$ where $i$ corresponds to day and $k$ corresponds to year. The claim size is defined as follows,

$$X_{i,k}(\tau_{1,k},\tau_{2,k}) = h_i \text{abs}(\min(\text{DAT}_{i,k} - E, 0) =, \quad i \in (\tau_{1,k},\tau_{2,k}), \tag{13}$$

where $CDAT_{i,k} = DAT_i + DAT_{i-4}$, $h_i$ is daily tick value corresponding to the claims. Obviously, $X_{i,k} = 0$ means no claim occurred. Hereby, summing the daily claims, $X_{i,k}$, of $k$th year, over the period of coverage, $(\tau_{1,k},\tau_{2,k})$, the annual claims per year $k$

are found as follows

$$X_k = \sum_{i=\tau_{1,k}}^{\tau_{2,k}} X_{i,k}, \tag{14}$$

Note that in this thesis we calculate the hypothetical daily payouts (claims), denoted by $X_{i,k}(\tau_{1i,k}, \tau_{2i,k}) = X_{i,k}$, from 1988 to 2019 (over $k = 1, ..., 31$ years) (see Section 4.3).

### 3.5.2 Viability of the DAT index

In case of inclusion of DAT index into the construction of a payout design, simple visualization tools to investigate the correlation of the DAT index and the crop yields will not provide reasonable picture, that would help an insurer to make conclusions about the features of movements in their dynamics. This fact can be explained the same way as in case of CDAT index viability checking: DAT index is measured daily, whereas the crop yield is estimated once its harvested (1 time a year). This type of visual inspection could only be conducted if WI was converted into singe measure (e.g., if we find maximum or minimum or median of DAT within the whole insured period, so that we will have only 1 value representing the DAT, or within the i-th month, but then we, again, can plot the yearly values of yield against the value of DAT for 1 month).

However, the weather variability, being that source of risk that is impossible to control, implies that for the WII product to be valuable for the farmer and profitable for an insurance company, an actuary should use as much information, describing particular weather condition, as it is available, whether for constructing the WI or for constructing the payout design. Also, those options of claim designs, which are based on daily average temperatures, envisage that farmer will receive payments immediately after the hedged WI is triggered.

The simplest construction of a payout design, based on DAT index, would have similar structure to the put/call option payoff function. But the usage of daily temperatures in the designs of WI will be inevitably accompanied by the randomness in both: incurred claim severities and their frequencies. For insured farmer(s) WII contract based on DAT should seem more transparent, as daily data about the temperature is, in general, available, so that farmer can track the number of payouts which are due to be paid in his favor. Whereas for an insurer the estimation of efficiency of these type of WII policies and the reserves needed to be able to sell these policies and stay solvent is highly challenging.

# 4 Pricing the Temperature Index Insurances with Hypothetical Parameter Values

Our constructions of a claim design as well as assumptions about the parameters included in formulas are experimental, in real life implementation we assume that they will be changed according to the more realistic and scientifically justified assumptions. We also did not implement any threshold that would restrict the claim size, meaning that in our study the claim size will be equal to the actual payment made in favour of an insured farmer.

## 4.1 Monthly ADAT Index Insurance

Our definitions of trigger values for this particular structure of a claim size design are more hypothetical and, therefore, can be transformed according to the features of a crop insured, species of the crop insured etc. However, in this particular example we focus on data describing Tartu county and the crop is the winter wheat. Hereby, given the formulas (11) and (14) the insurer will need to define the cover period (which we have) and for all $i$ estimate the monthly triggers $E_i$ and the monthly ticks $h_i$. For our hypothetical example they are given in Table 4. Graphs for various triggers by month are given in Annex C. To define the triggers, we decided to use long-term monthly averages of monthly ADATs, corresponding to each i-th insured month. In the future, this assumption about the trigger values can be revisited, i.e., if we have a scientifically proven facts about potentially harmful monthly average temperature for the crop, we would be able to set monthly triggers in accordance with those facts. These assumption about the definition of $E_i$-s also allows us to calculate the claim size taking into account the situations where there were sharp temperature drops, i.e., we earlier have mentioned 3 weather conditions that may cause the crop injuries: temperatures lower that the survival thresholds, long exposure to the temperatures near the survival temperature thresholds, sharp temperature falls after the prolonged period of smoothly decreasing\varying temperatures below 0 °C. Thus, by using the long-term average of a particular month's ADAT we will be able to take into account the negative impacts that potentially harmful low temperatures affect the winter wheat. For each month we set ticks ($h_i$). We set values of ticks hypothetically, because thick size calculation according to the formula (1) would require meaningful

Table 4: Monthly triggers (°C) and ticks for ADAT index based design.

| Month $i$ | October | November | December | January | February | March |
|---|---|---|---|---|---|---|
| $E_i$ | +5.87 | +0.87 | -2.39 | -4.05 | -4.2 | -0.5 |
| $h_i$ | 100 | 200 | 350 | 530 | 550 | 230 |

maximum payout values, but we believe that they can be only defined together with the specialist in agricultural results assessment. Although, tick values ($h_i$) presented in the Table 4 are hypothetical, the underlying assumption explaining the fact that ticks are different for each month was based, mainly, on the characteristics of winter wheat. That is, for those months where trigger value was below 0 °C we set higher payouts, considering that, as during December, January and February the lowest daily average temperatures occur, the loss of winter wheat yield can be more gradual, than within those months (corresponding to October and March) where trigger value was above 0 °C . Also, as $h_i$ represents the monetary value of each degree of deviation of monthly ADAT below the trigger. According to the graphs presented in Annex B, the quantity of intersection points between the index values and pre-defined hypothetical triggers are relatively large. This fact, on the one hand, will cause high frequency of claims and, on the other hand, the more the monthly ADAT deviates from the trigger, the bigger the claim size will be.

Monthly claims are obtained from formula 9. Summary of monthly claims with parameter values corresponding to Table 4 are provided in Table 5.

Table 5: Monthly ADAT index based claim sizes during 1988 - 2019

| n | Min. | 1st Qu. | Median | Mean | 3rd Qu. | Max. |
|---|---|---|---|---|---|---|
| 84 | 260.6 | 4946.4 | 13971.1 | 28930.6 | 45034.6 | 159634.3 |

The corresponding histogram of monthly claims is presented in Figure 6.

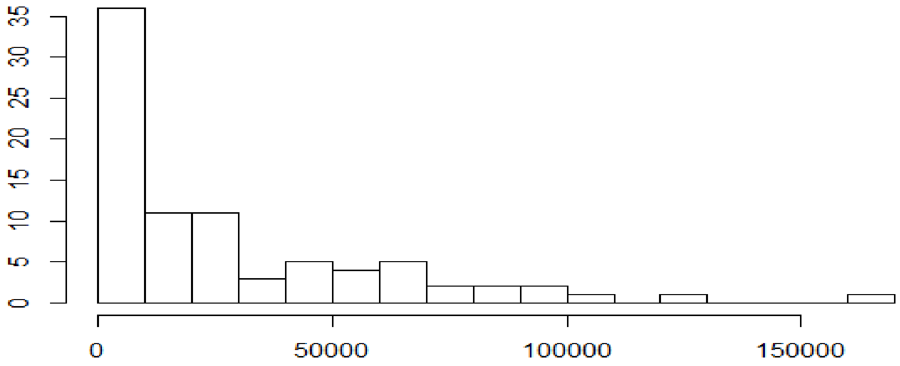

Figure 6: Monthly ADAT index based claim sizes during 1988 - 2019

Note, that within 6 months policy period such claims can occur each month, independently from each other.

Annual claims (over the 6 months period of coverage) are found by formual 3.3.1. Summary of annual claims with parameter values corresponding to Table4 are provided in Table 6.

The histogram corresponding to annual claims is presented in Figure 7.

Table 6: Annual (monthly values summed over the period of coverage) ADAT index based claim sizes during 1988 – 2019

| n | Min. | 1st Qu. | Median | Mean | 3rd Qu. | Max. |
|---|---|---|---|---|---|---|
| 31 | 800.6 | 28001.8 | 64817.3 | 83492.0 | 115355.9 | 258021.1 |

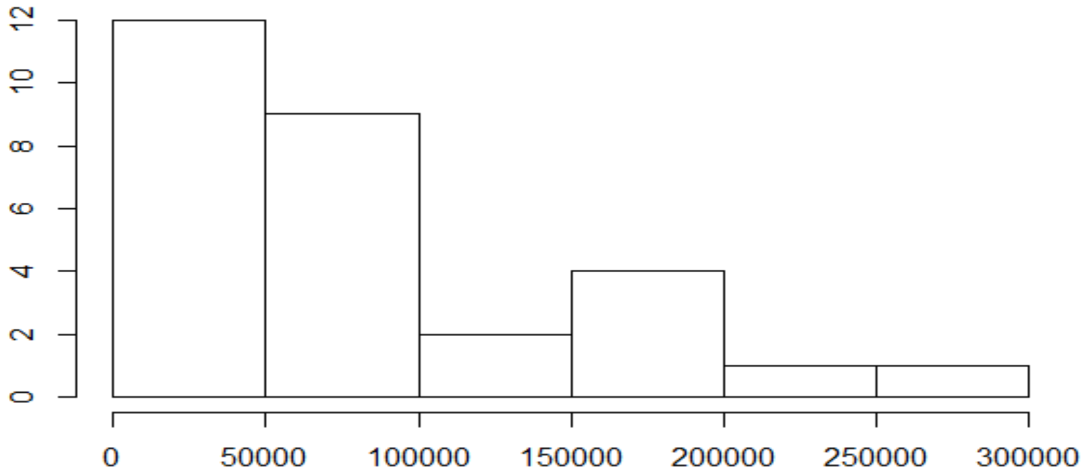

Figure 7: Annual (daily values summed over the period of coverage) ADAT index based claim sizes during 1988 – 2019.

### 4.1.1 Historical Pricing

As we mentioned in the Chapter 1, the concept of WII implies that the insured person should get a payment relatively faster, than if he or she bought traditional indemnity-based insurance product, in case if the weather index defined in the contract exceeds\falls below the trigger level. However, to simplify our premium calculations, we consider that the payout of all monthly claims is at the end of policy, at time March 31 (while policy has started October 01 previous year). For monthly claims we got 89 values (referring to all monthly non-zero values in (9) over all months in 1988–2018(19) ) and annually we got 29 claims claims to be paid (to all annual non-zero values in (3.3.1) over all 31 years in 1988-2018 ).

Based on Table 5 the empirical mean of monthly claims in 1988-2019, denoted by $\overline{X}$, was estimated to be 28 930.59 units of monetary units per 1 ha. For simplicity, we payout is made at the end of period of coverage. Hereby, the historical pricing based on monthly claims for the 6-month period policy gives premium

$$P = 6\mathrm{e}^{-0.5\delta}\overline{\mathrm{X}} = 6\mathrm{e}^{-0.5\delta}28\ 930.59$$

where $\delta$ corresponds to annual force of interest.

Based on Table 6 the empirical mean of annual claims in 1988–2019, denoted by $\overline{X}$, was estimated to be 83 492.0 units of monetary units per 1 ha. Historical pricing based on annual claims (over 6 months period of coverage) gives premium

$$P = \mathrm{e}^{-0.5\delta}\overline{\mathrm{X}} = \mathrm{e}^{-0.5\delta}83492.0$$

where $\delta$ corresponds to annual force of interest. Risk loading calculation and the interest rate were unchanged.

### 4.1.2 Pricing via Index Modelling

From the histogram of the ADAT index based monthly claim sizes in Figure 9, one may propose exponential, Pareto, gamma or Weibull distributions for modelling of the claim severities, as these distributions are frequently used for finding claim sizes distribution. The results of fitting are presented in the Figure 8. Empirical and theoretical CDFs of monthly claim sizes are given in Figure 9.

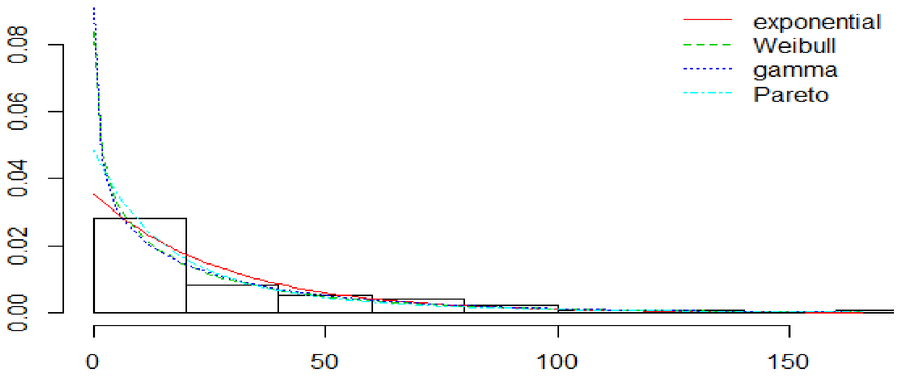

Figure 8: Modelling monthly claims ADAT index based claims via various distributions.

It is challenging distinction between the goodness of fit of all those distributions graphically. For more precise results we apply Akaike information criterion (AIC). Suppose that we have a statistical model (distribution) of some data. Let $p$ be the number of estimated parameters in the model (in our case, for distribution). Let $\hat{L}$ be the maximum value of the likelihood function for the model. Then the AIC value of the model is the following (e.g., Burnham& Anderson, 2002),

$$\mathrm{AIC} = 2p - 2\ln(\hat{L}) \tag{15}$$

According to the Table 7, the smallest AIC value belongs to the assumption that data comes from the Weibull distribution. Considering the conclusions of the fitting procedure, we decided that the Weibull distribution was better guessing for the distribution of our

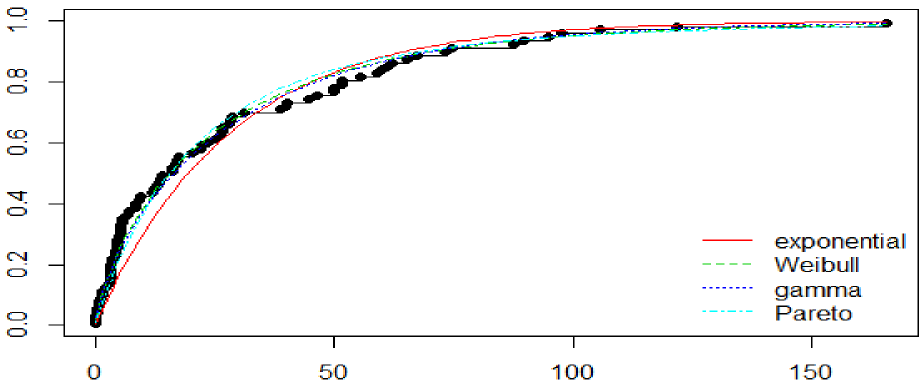

Figure 9: Empirical and theoretical cumulative distribution function of monthly claim sizes.

Table 7: Goodness of fit for ADAT index based claims

| | Exponential | Weibull | Pareto | Gamma |
|---|---|---|---|---|
| AIC | 735.303 | 731.288 | 734.974 | 731.341 |

particular sample. Recall the density with parameters, scale - $\lambda$ and shape $k$, of Weibull distribution has the following formula

$$f(x;\lambda,k)=\begin{cases}\frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1}e^{-(x/\lambda)^k} & x\geq 0,\\ 0 & x<0.\end{cases} \tag{16}$$

Estimates[9] to the parameters turned out as follows: $k$ was estimated to be equal to 0.819, $\lambda$ was estimated to be equal to 26 441. It turned out that, assuming the Weibull distribution assumption holds, the index model estimated expected claim is 29455.89 which is quite similar to empirical mean value. Hereby, the historical pricing based on monthly claims for the 6-month period policy gives premium

$$P=6\mathrm{e}^{-0.5\delta}\overline{\mathrm{X}}=6\mathrm{e}^{-0.5\delta}29455.89$$

where $\delta$ corresponds to annual force of interest.

## 4.2 Daily CDAT Index Insurance

Period of coverages for calculating *CDAT* relies on the same assumption about the period of coverage as was used for calculating the claim size based on the ADAT index with an inclusion of April DATs; Consequently, the number of days $i$, reflecting temperature drop between the $5^{th}$ and the $1^{st}$ DATs during all years of available information, results in 6 652 data points (against trigger).

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[9] The values of estimates are obtained by implementing the maximum likelihood by R package `mle`.

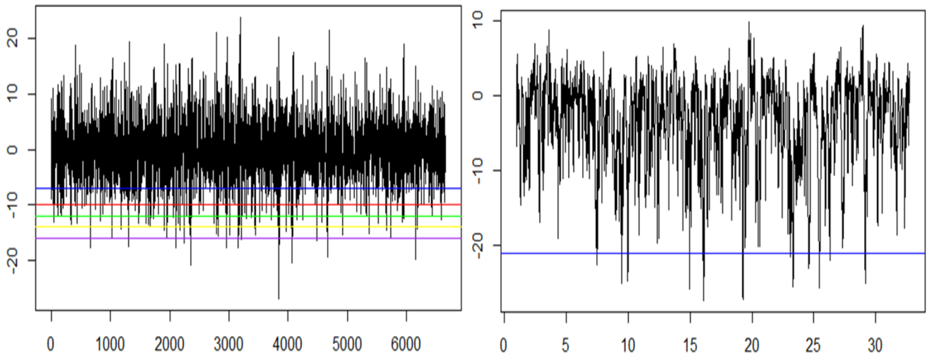

Figure 10: Daily CDATs (on the left panel) and daily DATs (on the right) intersections with triggers.

The conclusion made from visual inspection of Figure 10 is, generally, the that the number of payouts for both options of a claim size design is highly affected by pre-defined trigger levels. According to the graphs presented on the Figure 10, we can conclude that the number of claims due to the low temperatures, which may injure the crop is rather small, whereas claims' severity and frequency, which may come from those farmers whose winter wheat seedings were insured against significant temperature falls, varies a lot due to different triggers.

For the for the construction of a CDAT claim design described by formula (11), we have defined various trigger levels which are equal to: -7°C, -10°C, -12°C, -14°C, -16°C, taking into account that the maximum drop was established at the level of -26.9°C. We also allow that these triggers can be specifically defined for each particular period. Hypothetical trigger values were set, assuming that, with the assistance of agricultural results assessment specialists, an insurer will be able to define what is the actual harmful temperature drop for the winter wheat seedings and during which time frame it should occur so that farmer will experience losses of winter wheat yield. Additionally, we allow the possibility that an insurer can change the triggers by decreasing or increasing the scale of degree changes.

For the illustrative purposes we decided to implement formula (1) for computing the money factors $h_1$. However, we still think that, although it is possible to set reasonable trigger and exit values, we will not restrict the claim sizes according to the hypothetical maximum payouts (which we have use for computing triggers).

We are interested of annual (over the period of coverage) CDAT index based claims. We use formula (14). Histogram corresponding CDAT annual claims is given in Figure 11.

It turned out, the number of (yearly) claims incurred, within the insurance policy, based on C5DAT index, equals 31, which means that there were no years without paid claims (if

Table 8: Daily ticks for various daily triggers for the period October–April for the CDAT policy

| | Design 1 | Design 2 | Design 3 | Design 4 | Design 5 |
|---|---|---|---|---|---|
| max payout | 1000 | 1000 | 1000 | 1000 | 1000 |
| exit($^\circ C$)$S_{CDAT}$ | -18 | -18 | -18 | -18 | -18 |
| trigger ($^\circ C$)$E_{CDAT}$ | -7 | -10 | -12 | -14 | -16 |
| $h_i$ | 90.911 | 125 | 166.67 | 250 | 500 |
| nr of claims | 528 | 196 | 108 | 53 | 23 |

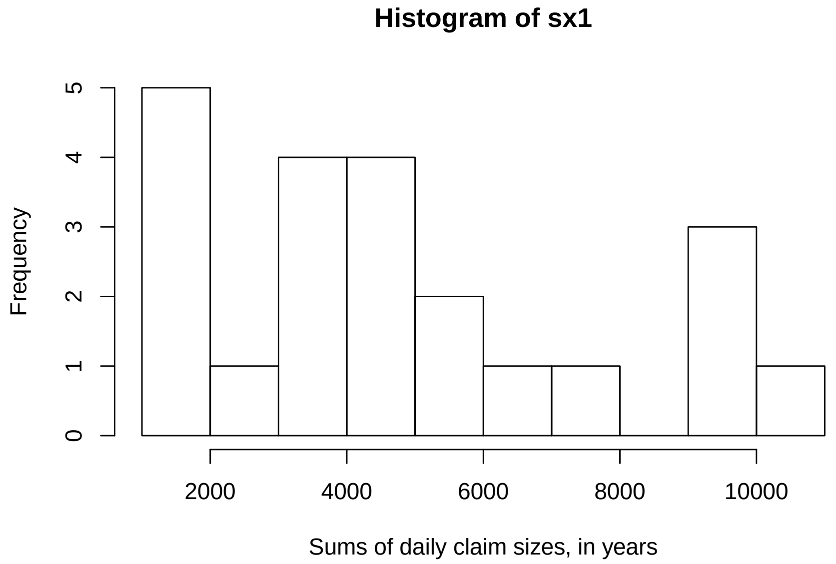

Figure 11: Annual (daily values summed over the period of coverage) CDAT index based claim sizes during 1988 – 2019

we do not take into consideration the policy year starting in 1987, i.e., 9 claims incurred within this policy year). The empirically estimated average value of (yearly) claim sizes, calculated by (13), and based on CDAT index, equals to 4 803.322.

### 4.2.1 Historical Pricing

For historical pricing calculations we use Design 1 in Table : trigger is $E_{CDAT} = -7$ with exit $S_{CDAT} = -18$. For simplicity we assume that the payout is at the end of policy period (while in reality it can be daily, weekly, monthly). The policy period is 7 months, while expected loss we take the mean of hypothetical claims (which is in response to trigger $E_{CDAT} = -7$ with exit $S_{CDAT} = -18$. Hereby,

$$P = \mathrm{e}^{-\frac{7}{12}\delta}\overline{\mathrm{X}} = \mathrm{e}^{-\frac{7}{12}\delta}4803.322,$$

where $\delta$ corresponds to annual force of interest.

Risk loading calculation and the interest rate were unchanged.

### 4.2.2 Pricing via Index Modelling

According to Figure 11 one can see that, within 31 year of given data about DAT, claims occurred every coverage period (if we exclude coverage period which started in October of 1987). Also, it seems that the yearly claim sizes, based on C5DAT index, are not distributed according to any of the classic regular distribution. It is more likely, that after one has plotted an empirical density of these claim sizes, two bell curves will show off, i.e., multimodal distribution should be the best option to consider.

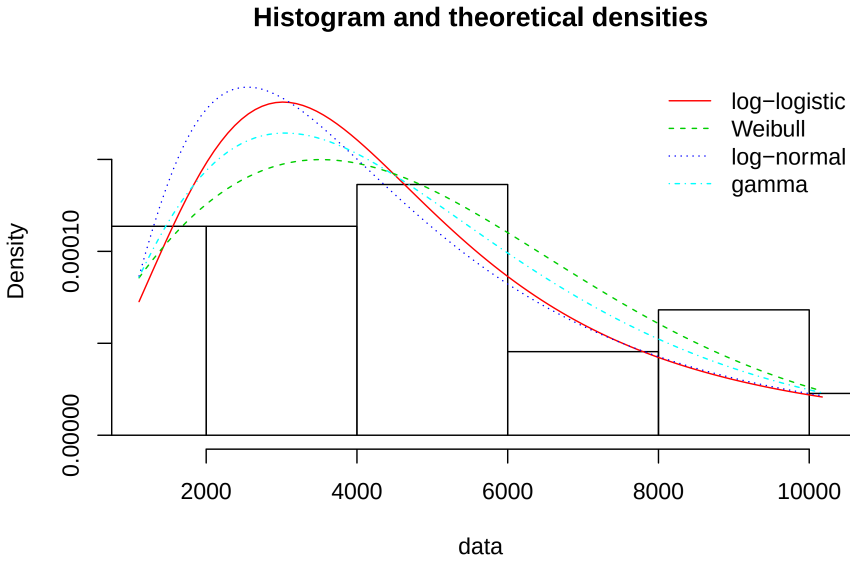

Figure 12: Modeling annual CDAT claims via various distributions.

Nevertheless, we still want to investigate which of the suggested distributions: loglogistic, Weibull lognormal or gamma, might fit the data, and estimate the average (yearly) claim sizes accords to the best fitted distribution. The main reason for our simplification is that, as climate shifts permanently and WI is dependent on the different trigger values, finding a unique mix of distributions (so that estimated average value will be equal to empirical average value of claim severities) may not give the same accurate results in the future.

Figure 12 shows that non of the suggested distributions properly fit the data. Although, Weibul distribution seems to be reasonable approximation in this case Figure 13, depicting empirical and theoretical CDFs, suggests, that indeed, non of the tested distributions can capture the patterns in the (yearly) claim severities distribution, especially on the right tail.

Graphically it is challenging to make a distinction between the goodness of fit of all

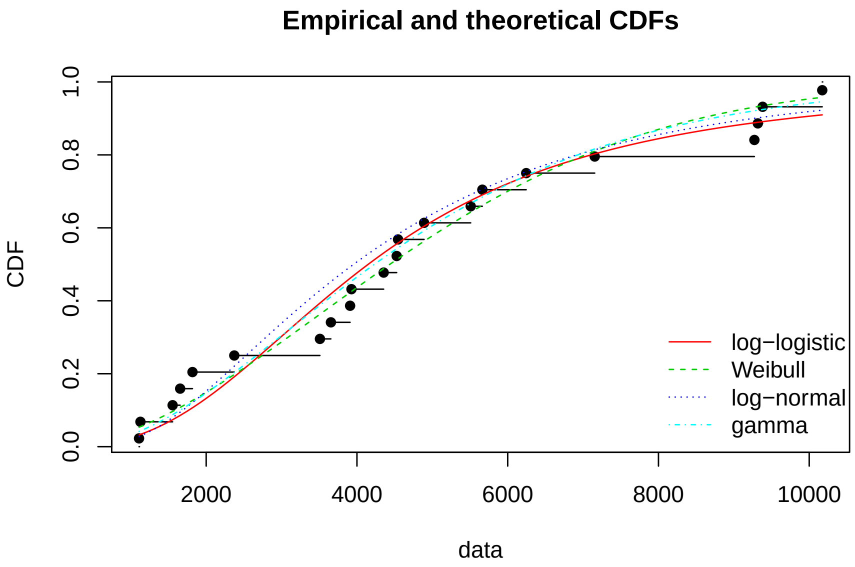

Figure 13: Modeling annual CDAT claims via various distributions.

thb!

Table 9: Goodness of fit for CDAT index based claims

| | log-logistic | log-normal | Weibull | gamma |
|---|---|---|---|---|
| AIC | 414.0075 | 412.8613 | 411.2211 | 411.4461 |

those distributions. For more accurate result the Akaike information criterion (AIC), given by (15). Smallest AIC value corresponds to best fit. The AIC values[10] for underlying distributions in Figure 12 are given in Table 9. According to the Table 9, the smallest AIC value belongs to the assumption that data comes from the Weibull distribution. Considering the conclusions of the fitting procedure, we decided that the Weibull distribution was better guessing for the distribution of our particular sample. Estimates[11] to the parameters turned out as follows: $k$ was estimated to be equal to 1.837, $\lambda$ was estimated to be equal to 5 468.92. Hereby, the mean by index pricing is 4858.968. Hereby,

$$P = \mathrm{e}^{-\frac{7}{12}\delta}\overline{\mathrm{X}} = \mathrm{e}^{-\frac{7}{12}\delta}4858.968,$$

where $\delta$ corresponds to annual force of interest.

# 5 Conclusion

Within the framework of our study, we described the concept of weather index-based crop insurance, we also provided an information about advantages, disadvantages and

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[10] The values of AIC are obtained by implementing the maximum likelihood (MLE) by R package `mle`.

[11] The values of estimates are obtained by implementing the maximum likelihood by R package `mle`.

challenges corresponding to this concept. Even though, WII products allow to minimize some of the issues related with traditional indemnity-based insurance products (e.g., moral hazard, adverse selection), there are some specific challenges which makes further development of weather-index based insurance products relatively difficult. Basis risk, which occurs due to the distance between reference weather station and insured areas (regions, farms), is the reason behind the cases when farmer experienced the crop yield losses but the payment wasn't made (and vice versa). Also, tremendous number of researches scientific researches about the development of new weather indexes, discovering the features of particular species of a crop and their sensitivity to different weather variables, extensive agricultural statistics and partnership with government, should be donein order to create, viable pilot of WII product.

Within this study we applied two pricing methods: historical pricing (burn analysis) and index modelling. The first method, being a rough guideline, rather than the accurate baseline, is based on calculation of empirical mean value of claims incurred. Index modelling method implies, that we suggest and fit distributions to the historical claim sizes data and if the distribution is found then we calculate the mean value accords to the estimated distribution's parameters (we used maximum likelihood method for estimating parameters of a distribution).

Beforehand, for the sake of illustration, we created three experimental constructions of payout designs with hypothetical parameters and temperature-based weather indexes: (monthly) average of daily average temperature index (ADAT), (5 days) change in daily average temperature (C5DAT) and (every day) daily average temperature (DDAT). Weather indexes were constructed, using the daily average temperature (DAT) data collected by Tartu Tõravere meteoroloogiajaam during 1988-2019 and kindly provided by Estonian Weather Service (2019). ADAT index is mainly aimed to insure the crop (features of winter wheat were specifically considered) against low daily temperatures, but the temperature values become much smoother; C5DAT index was developed in order to reflect potentially harmful “sharp” DAT drops (i.e., temperature variability); DDAT index should provide a coverage for the crop yield losses caused by extremely low daily average temperatures.

Additionally, we tried to check if the dynamics of chosen weather indexes (ADAT, C5DAT, DDAT) and yearly winter wheat yields demonstrate similar patterns, simply plotting historical data of one variable of interest against another one. Even though this method of visual inspection still can be used, in those cases where both values correspond to the same time format, conclusions based on it are subjective and do not explain the causation. However, weather index-based crop insurance concept implies that, to be attractive weather risk-mitigation tool for a farmer and profitable product for an insurer, the insured crop should show relatively high sensitivity to the deficientvalues of the weather variable(s), reflected by the WI, which characterize the weather conditions of to-be-insured area where the crop(s) is cultivated. Thus, one of the main challenges for an insurer and for developers of WII concept, on the way to creating a viable weather index-based insurance product, is to, rather, check the sensitivity of the crop to the existing weather index(es) or to create new weather index, assuming that it captures one (or several) characteristics of the crop and translates it so that it will represent potentially harmful weather condition for the crop. Each of these two options has its pros and cons. To implement the first option an insurer will still need to set meaningful parameters (e.g., triggers, strikes). Definition of these values is also difficult because the relation between meteorological events and sustained losses has to be accurately established and quantified. The creation of a new weather index is, undoubtedly, requires new scientific researches dedicated to the analysis of reliability of the index and its superior advantages in comparison with already existed indexes.Although, the number of possible index combinations has no particular limits, because there are various options of: WI and underlying weather variable(s), triggering measurements, coverage period durations and types, payout structures.

After the results of implementation of historical pricing and index modelling were derived, we could conclude that these methods gave similar results (even if the fitted distribution showed the lack of fit). Although the historical pricing method is straightforward and purely data-based, i.e., no additional data insights are incorporated in the calculation of average value of claim sizes, it is more preferable in comparison with pricing WII with index modelling method (i.e., fitting distributions to historical claim sizes). The main reason explaining this conclusion is, that having very small sample of values, corresponding to (yearly) incurred claims, the procedure of fitting more complicated (multimodal) distributions is of moderate relevance. It would be justified only if trigger(s) and maximum payout were set as accurately as possible. However, both of these methods do not allow to take into consideration an assumption that climate shifts are permanent, i.e., an actuary can't create and use a dynamical model of the underlying weather index within the concept of those pricing methods. Therefore, even though an actuary can find a unique distribution for modelling claim severities, as climate changes, new incurred claims may not follow patterns described by that distribution.

Relying on the results of implementation of two pricing methods for WII product, we can assume that an insurance company, which uses historical pricing or index modeling to find an average value of claim sizes, will probably face with a necessity to mitigate uncertainty, due to the climate changes which can't be precisely captured, by adding markups to the value of premium. However, as WII is considered to be less costly, in a sense that no on-farm loss assessment is needed, additional markups can mitigate this particularly relevant distinction for the insured party. Nevertheless, Che Tiab and Benth (2012) implemented dynamical temperature modelling (based on time series of the weather variable) in their study, and stated that they derived better (hypothetical) results in comparison with index modelling and Burn analysis methods.

Finally, we would like to highlight that this study was aimed to provide an overview of the concept of WII and to implement two methods of valuation of WII product. The procedure of setting parameters, e.g., triggers, exits, needed whether for constructing the WI or claim design, requires adjustments which will reflect the weather parameters of the reference weather station. Moreover, weather index-based insurance contract which was specifically developed for species of a crop can not be directly introduced in another country/region and even area, thus, the process of initial design elaboration becomes relatively costly and time-consuming. Therefore we agree, that in the future, our conclusions can be revisited, but for further studies derived results might be of particular relevence.

# Appendixes

## Annex A

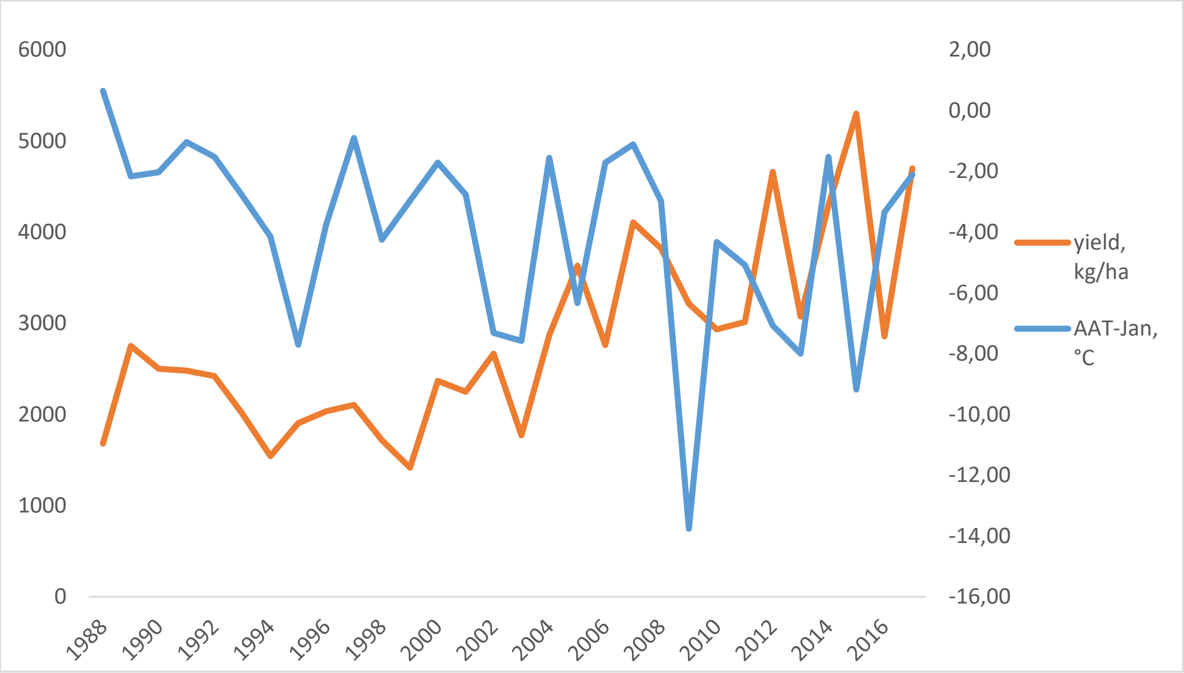

Fig.A.1. Dynamics of yearly yield data and AAT indexes for January

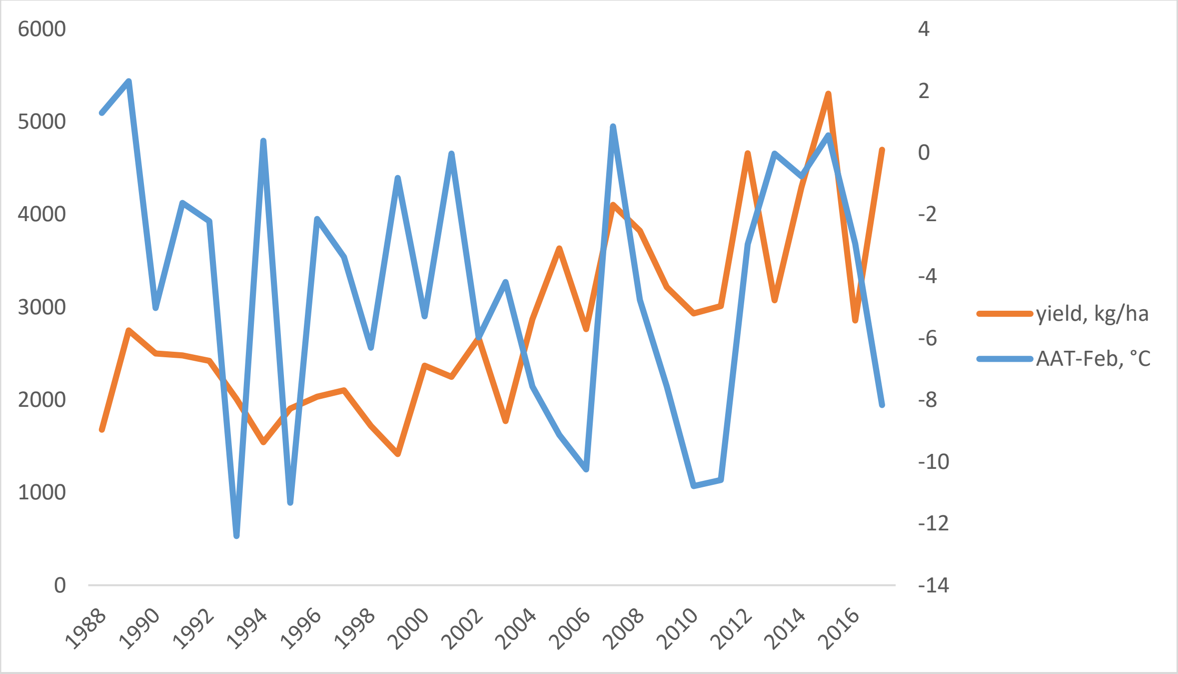

Fig.A.2. Dynamics of yearly yield data and AAT indexes for February

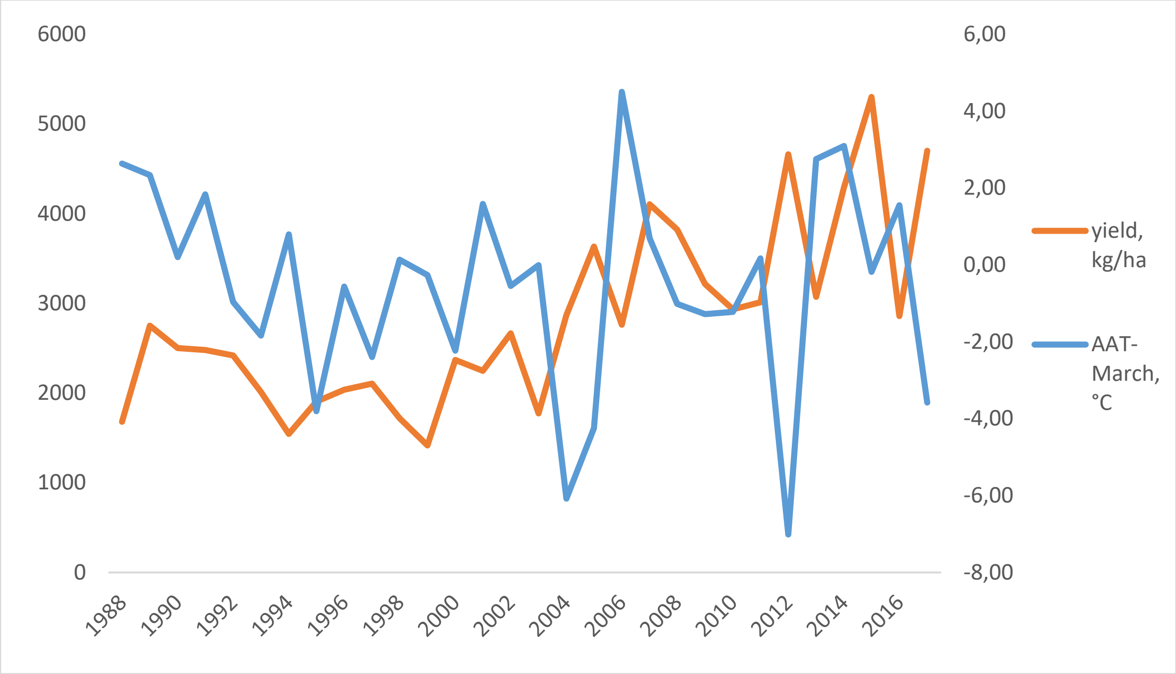

Fig.A.3. Dynamics of yearly yield data and AAT indexes for March

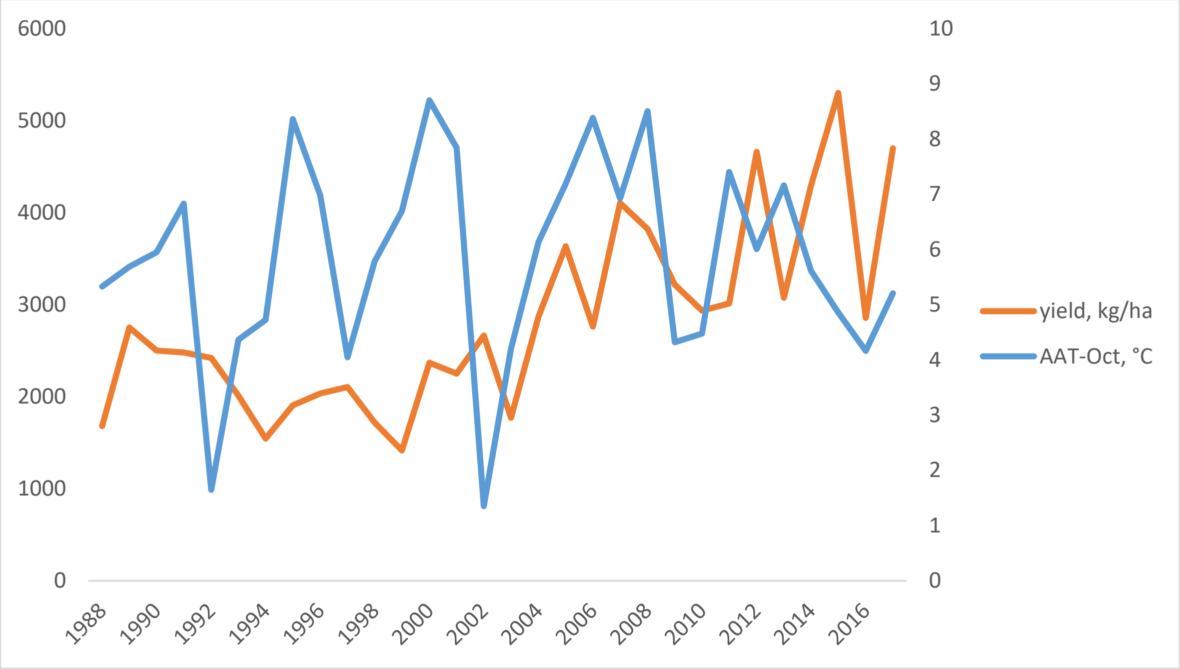

Fig.A.4. Dynamics of yearly yield data and AAT indexes for October

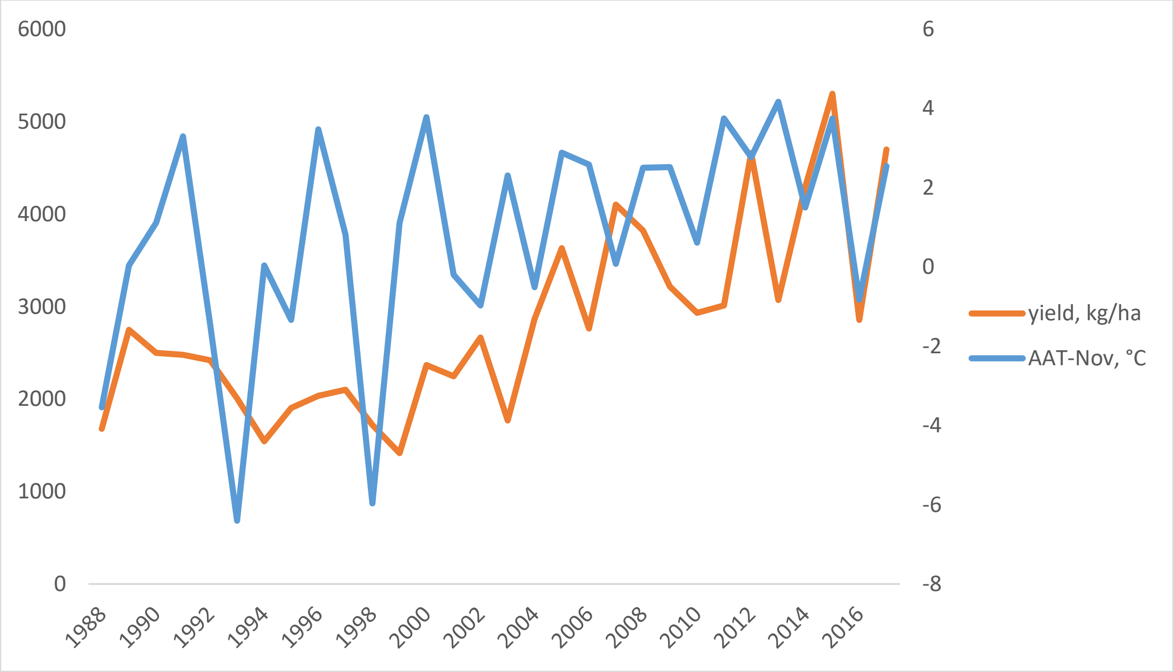

Fig.A.5. Dynamics of yearly yield data and AAT indexes for November

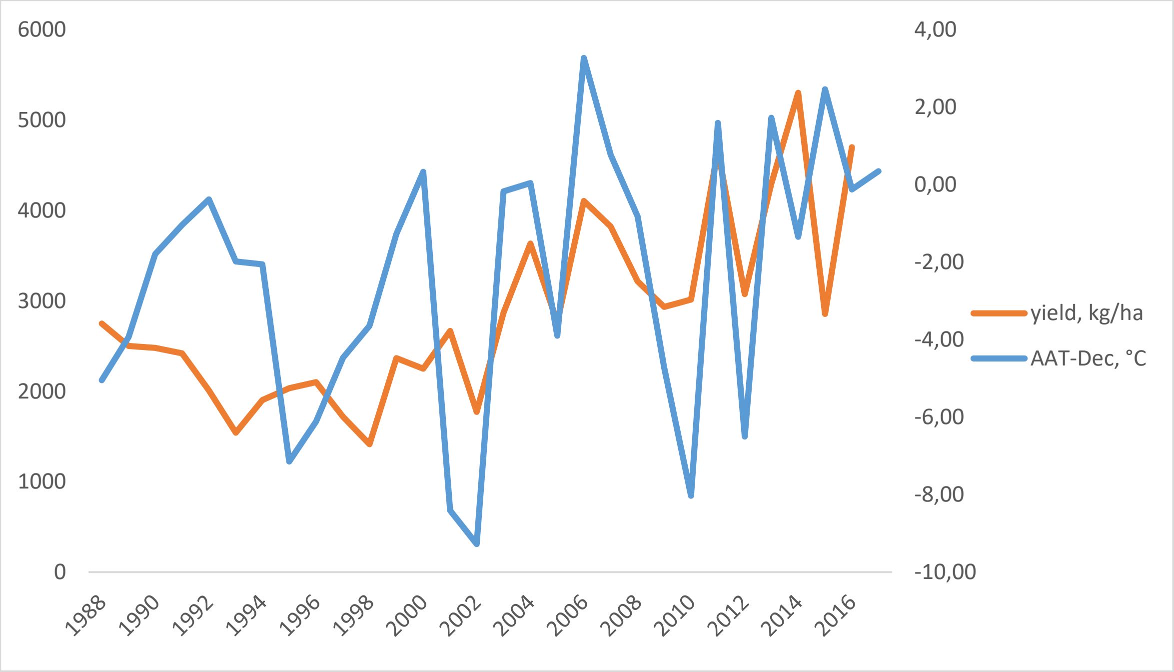

Fig.A.6. Dynamics of yearly yield data and AAT indexes for December

# Annex B

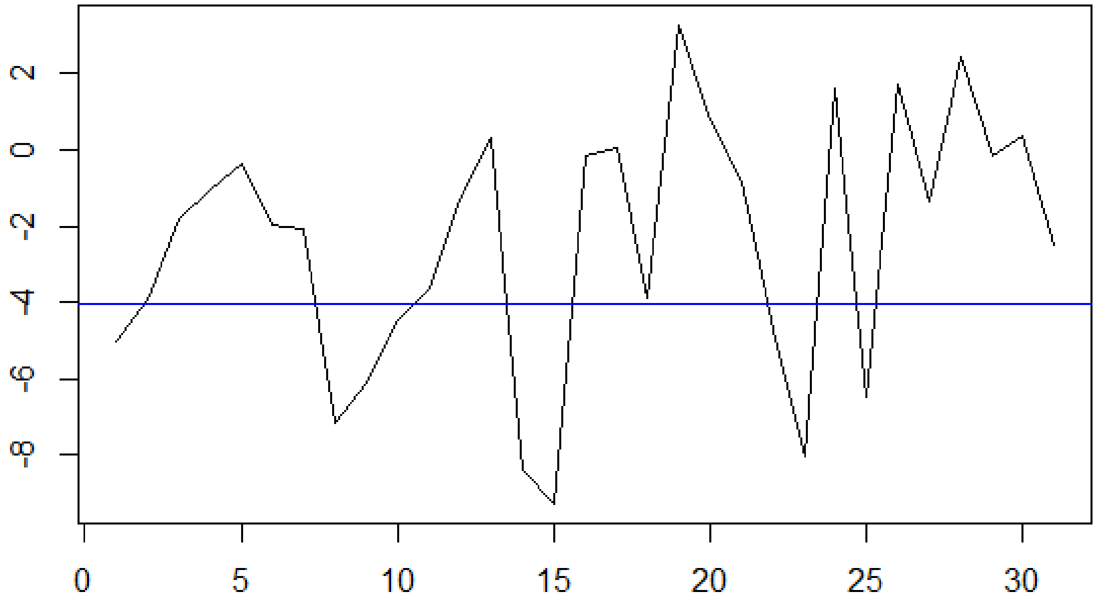

Fig.B.1. AAT indexes in January and corresponding trigger value $E_j$= -4.05°C (blue solid line)

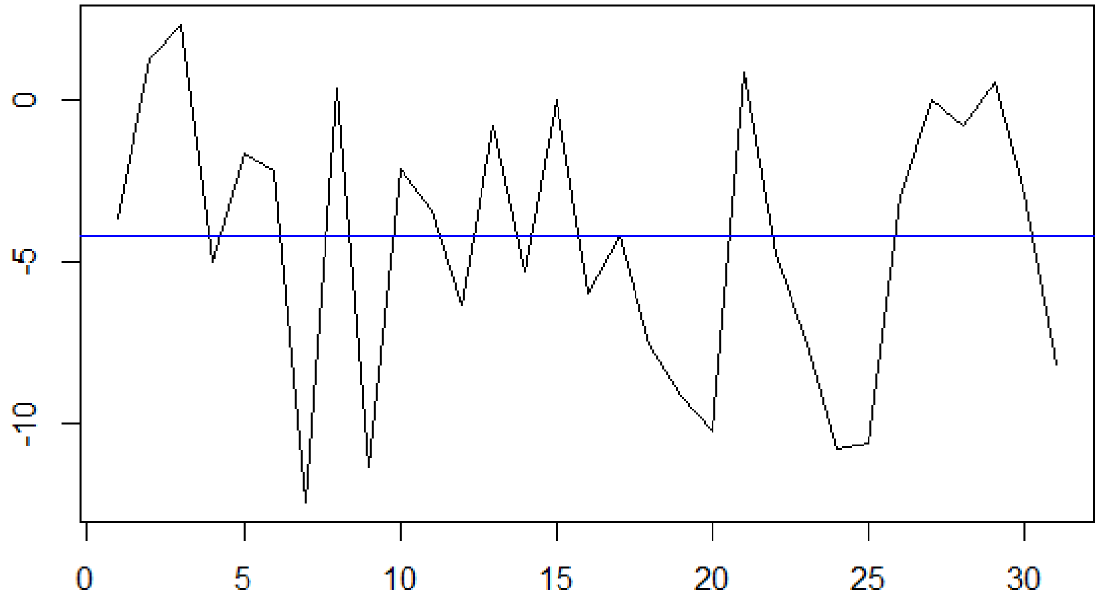

Fig.B.2. AAT indexes in February and corresponding trigger value $E_j$= -4.2°C (blue solid line)

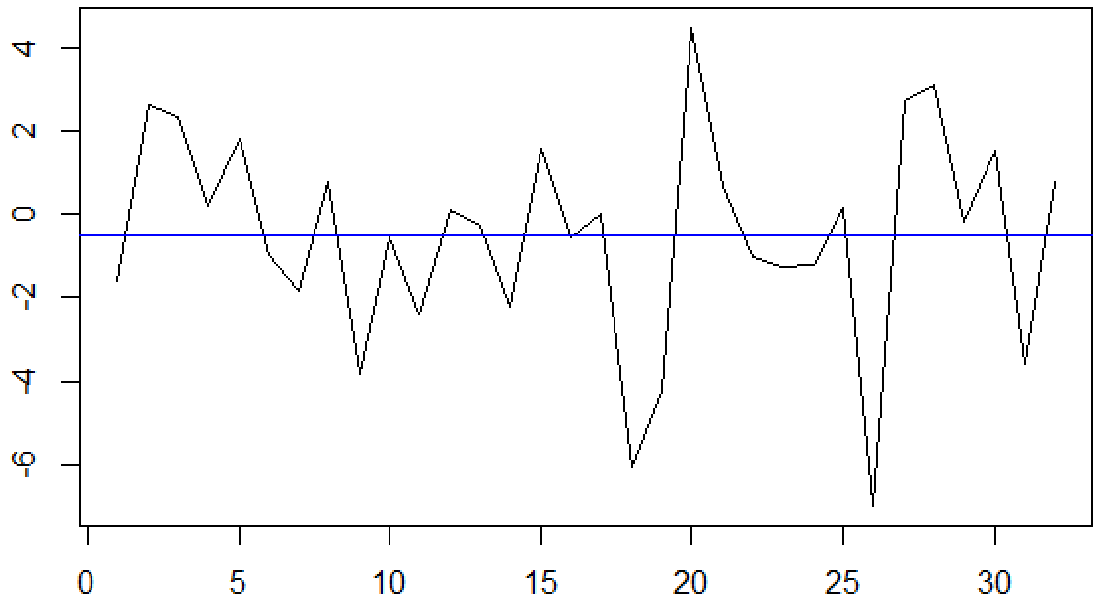

Fig.B.3. AAT indexes in March and corresponding trigger value $E_j$= -0.5°C (blue solid line)

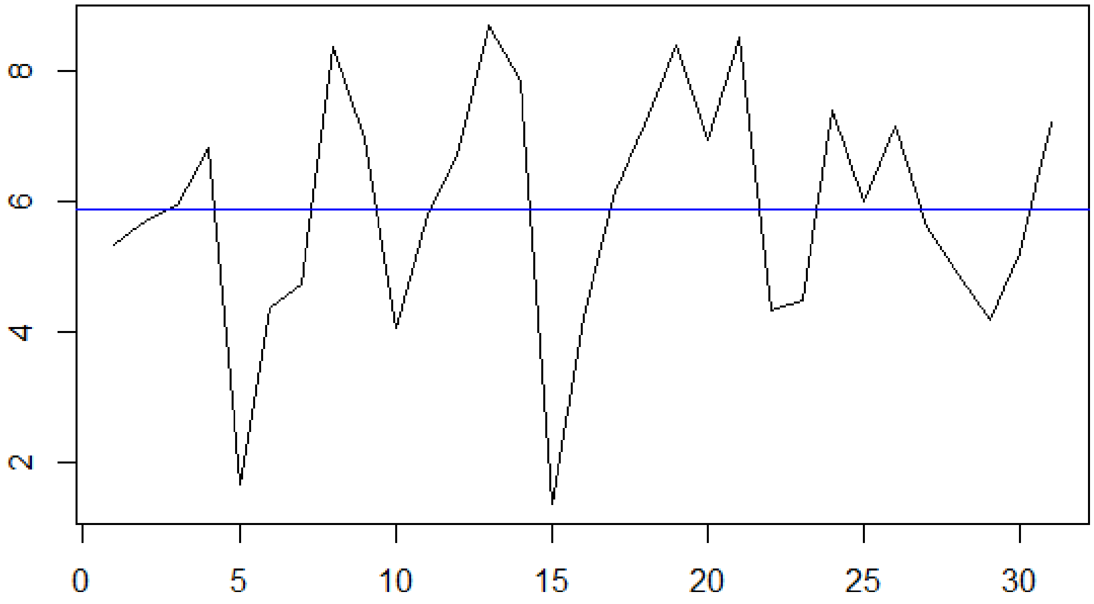

Fig.B.4. AAT indexes in October and corresponding trigger value $E_j$= 5.87°C (blue solid line)

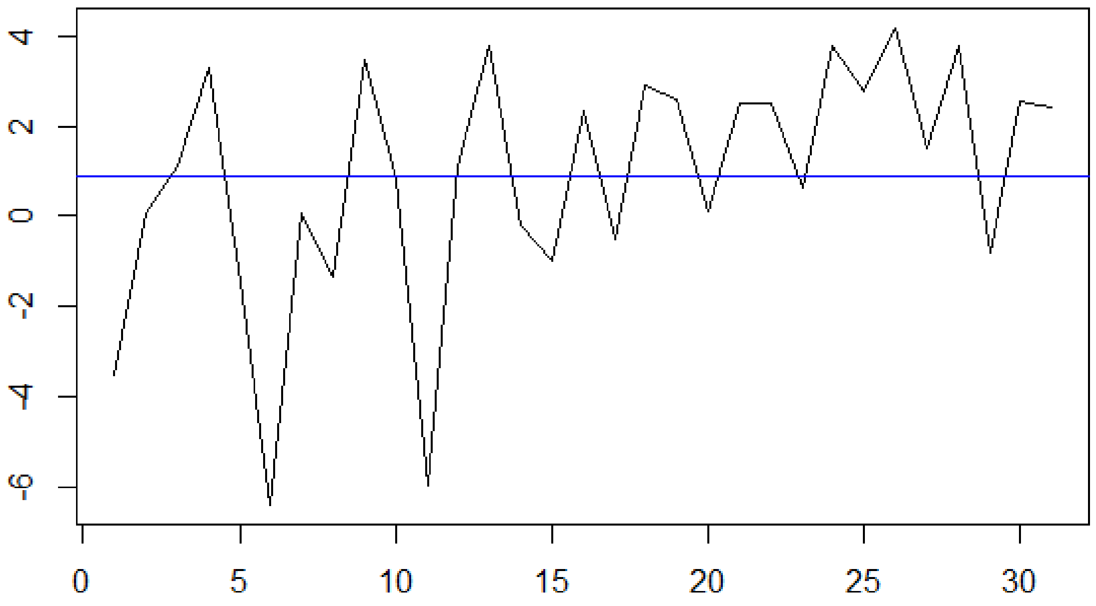

Fig.B.5. AAT indexes in November and corresponding trigger value $E_j$= 0.87°C (blue solid line)

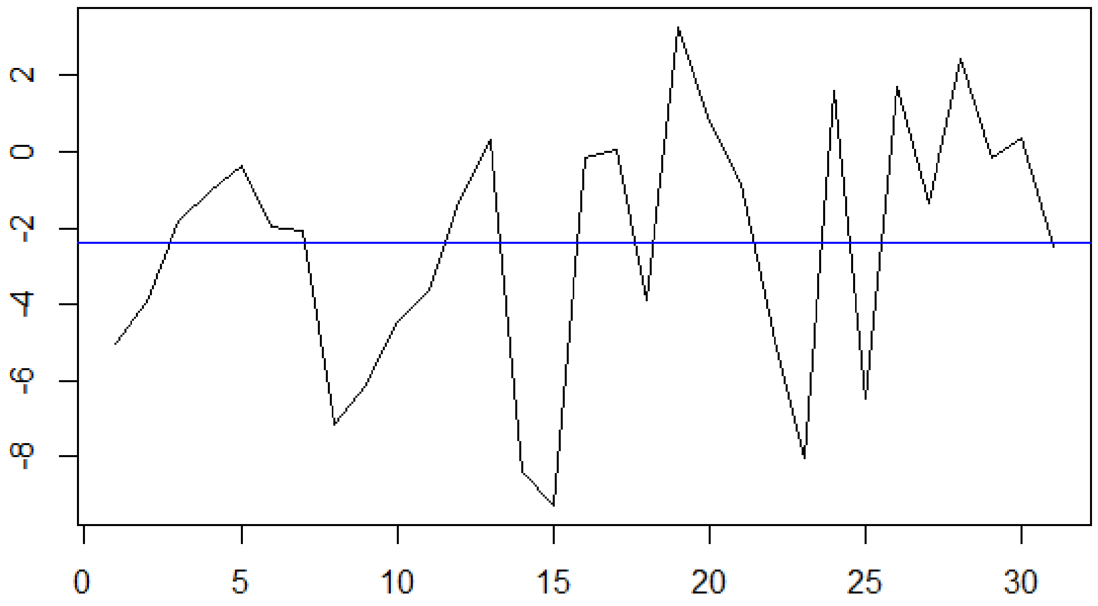

Fig.B.6. AAT indexes in December and corresponding trigger value $E_j$= -2.39°C (blue solid line)

# Annex C

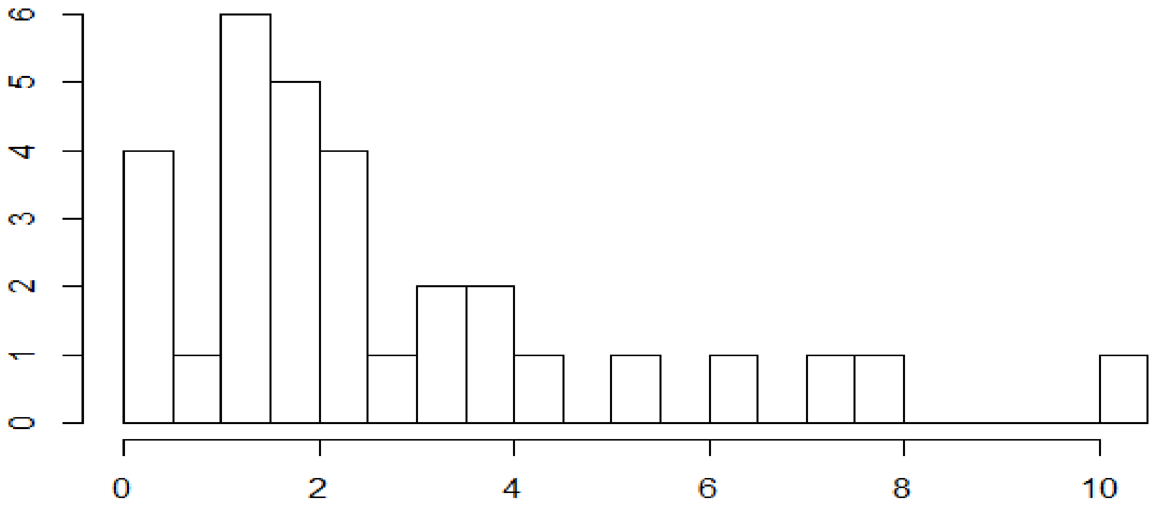

Fig. C.1. Histogram of yearly claim sizes $X_{1i}$ with trigger level $\mathrm{E}_1$= -10°C

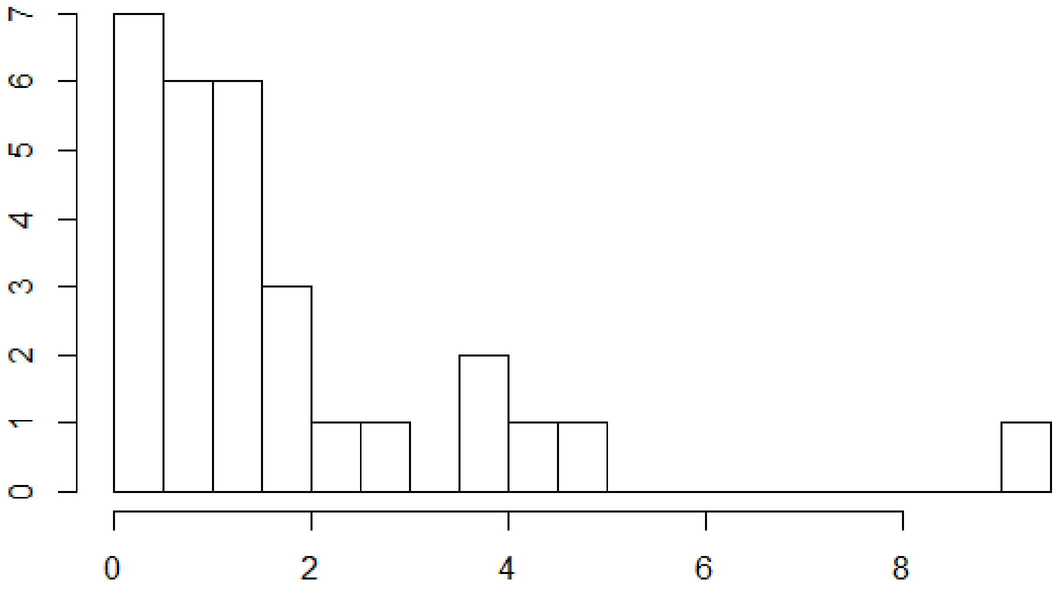

Fig. C.2. Histogram of yearly claim sizes $X_{1i}$ with trigger level $\mathrm{E}_1$= -12°C

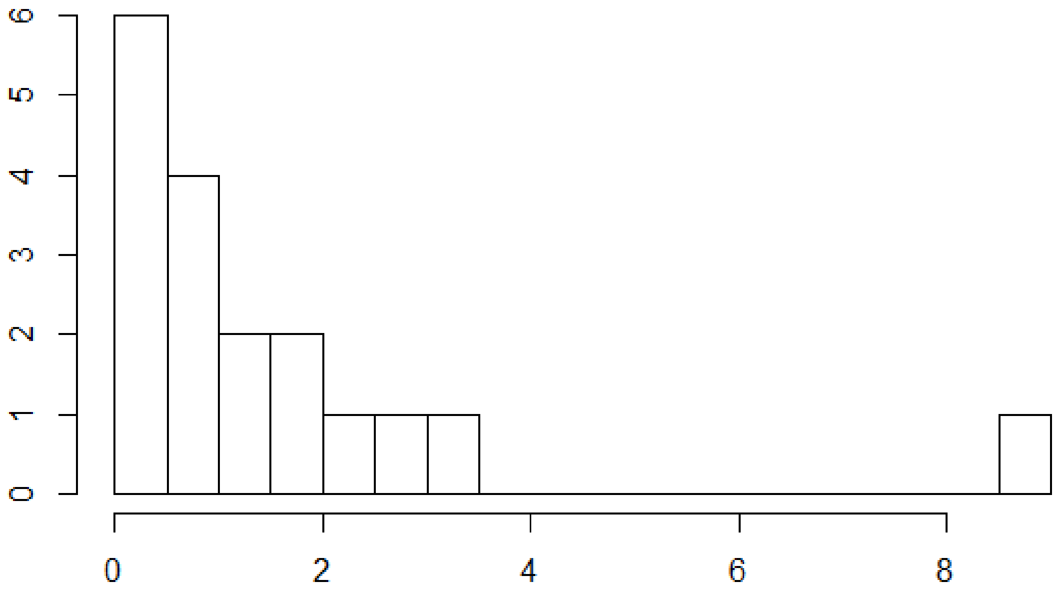

Fig. C.3. Histogram of yearly claim sizes $X_{1i}$ with trigger level $\mathrm{E}_1$= -14°C

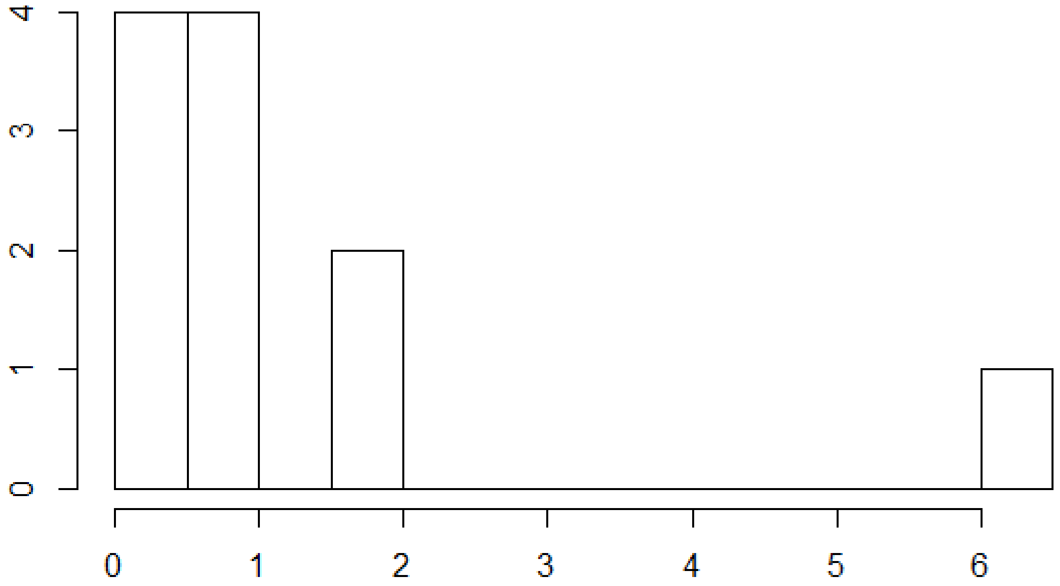

Fig. C.4. Histogram of yearly claim sizes $X_{1i}$ with trigger level $\mathrm{E}_1$= -16°C

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