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A Review of Methods Used to Measure Treeline Migration and Their Application

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ABSTRACT. Treelines define the upper limits of where trees are capable of growing. These exist at high elevations across many of the world's mountain ranges and at high latitudes across much of Russia and Canada. With climate change causing more favourable conditions for tree-expansion in many areas, these boundaries are moving to higher elevations and latitudes in many places. In this study we look at four of the more common methods used to track and monitor treeline changes, specifically dendrochronology, measurements of tree-diameter, repeat vegetation transects, and the use of photographs and remotely sensed imagery. We break down the various methods and discuss their reliability under various conditions. There are a few key parameters that determine the suitability of a method to measure treeline change, such as the accessibility of the study site, the availability of historical data such as photographs, notes or maps, the size of the area to be studied, and if the drivers of migration are of interest. Dendrochronology provides the most exact data and is the only methodology that enables correlation of treeline movements with climate change. However, using remote sensed data and repeat photographs is a quicker approach that allows larger areas to be studied. We highlight that no method is consistently superior but that the optimum method is largely site and scale dependent.

Keywords: dendrochronology, method selection, repeat photography, treeline migration, treerings, vegetation transect, vegetation chang

1. Introduction

Treelines, which indicate the boundary between trees and other types of vegetation, exist as vegetational transition zones in high mountain regions and at high latitudes. Treelines indicate a threshold of which above trees are no longer capable of growing and are dependent on local climate characteristics (Körner and Paulsen, 2004). Naturally occurring treelines primarily exist in cold areas and are often limited by low temperatures (Paulsen and Körner, 2014). The regions in which climate-restricted treelines are primarily located, such as high mountains and the Arctic, have experienced more rapid rates of warming compared to the global average (Nogués-Bravo et al., 2007; IPCC, 2014). For example, the Arctic has experienced a 24% increase in days with temperatures above freezing (Bhatt et al., 2010), while temperatures in the Swiss mountain regions has increased at approximately twice the magnitude compared to the mean trend of the Northern Hemisphere (Rebetez and Reinhard, 2008). The increase in temperature has led to an expansion of suitable habitat for trees in many regions. As a result, many of the world's studied treelines have migrated to higher elevations and latitudes (Harsch et al., 2009).

Treelines exist at varying elevation around the world and require a growing season of a minimum of 94 days, where the daily mean temperature does not drop below 0.9 °C (Paulsen and Körner, 2014). At a global scale, this means that treelines appearing along the same latitude will be at a roughly similar elevation, with a difference between the northern and southern hemisphere due to the slightly different temperatures between the hemispheres (Körner and Paulsen, 2004). There are, however, often local variations to treeline positions. Treelines appearing on different aspects of a mountain often vary in elevation due to microclimatic differences caused by the variation of shading and net incoming solar radiation (Wilson et al., 1987). While there is a clear correlation between temperatures and treeline positions around the world (Paulsen and Körner, 2014), there are many other local and regional factors that can prevent trees from growing in certain areas. This may be one of the main reasons as to why not all treelines experiencing warmer temperatures have migrated to higher elevations or latitudes (Harsch et al., 2009). These include biotic and abiotic factors such as snow cover (Esper and Schweingruber, 2004), moisture availability (Andersen and Baker, 2006; Autio, 2006), fires (Butler and Dechano, 2001), damaging frost events (Autio, 2006; Coop and Givnish, 2007) and insect outbreaks (Hofgaard et al., 2013). However, it may also be due to the inherent lag effect where trees are sometimes slow at tracking their suitable climate window (Payette, 2007).

The movement of treelines is dependent on the successful establishment and maturity of seedlings. This requires favourable growing conditions during many consecutive years. While

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overall growing conditions may be improving, just a few seasons of poor weather conditions, or even isolated events, can lead to seedling mortality. Hence, improved growing conditions can only lead to treeline migration if there is also an absence of adverse conditions for a longer period of time (Körner, 2012). Establishment of seedlings also depends on other biotic and abiotic factors. For example, the establishment of high latitudinal treeline is in some cases impeded by the presence of permafrost (Lloyd, 2005), while trees including many of the New Zealand Nothofagus require the presence of particular fungi in the soil for seedling establishment (Dickie et al., 2012). These factors may cause a delayed response of treeline migration. However, we should likely expect more treelines to show signs of expansion in the future as conditions continue to improve.

A wide range of methods has been used to measure and monitor the shifts of treeline positions around the world. As most treelines move at a relatively slow pace, these changes may not be noticeable over short timeframes. Long term monitoring of tree-positions or measurements of tree-age is therefore often required to spot these changes. Dendrochronology, which is the measurement and comparison of tree-rings (also called growth rings), is a popular approach in which trees can be dated to determine their approximate age. While this method provides a good indicator of past movements of treelines, it is invasive (Norton, 1998) and may not always be a feasible approach depending on the tree-specie (Grissino-Mayer, 1993). Selecting the most appropriate method is a critical part as we expand on the number of sites in which treeline dynamics are assessed. In this paper, we will firstly cover the methods most commonly used when studying treeline migration. After providing a brief introduction of these various methods, we will assess what factors influence the prefered method of choice and how to go about selecting the most appropriate one.

2. Methods of Treeline Measurement and Monitoring

There are several challenges associated with monitoring the location and movement of treeline positions, including their large spatial extent and often remote locations, the sometimes-diffuse gradient between forests and non-forested areas, as well as the slow movement of many treelines. While all methods can be used, studies that use a combination of different methods as these can provide complementary information. Repeat photography can be used in combination with experimental research methods, such as induced warming or altered atmospheric gas concentrations, to track both how treelines have moved in the past and how they are likely to respond to future climate change (Myers-Smith et al., 2011). This review paper does not aim to provide an exhaustive guide as to how all of the examined methods should be applied. Instead, this paper aims is to help the reader identify which method may prove to be the most suitable approach depending on the aim of the study, the resources available, and the local conditions of the study site.

2.1. Dendrochronology

Dendrochronology is versatile and has been used by archaeologists, ecologists, climate scientists and geologists alike (Schweingruber, 2012). It is based on the principle that trees around the world form annual growth rings, which will differ in width depending on the climatic characteristics of that particular year. Not only is this method used to reconstruct more recent climatic change, but utilising cores from preserved fossilised trees can allow for high-resolution climate reconstructions. Multiple records stretch back to the mid-Holocene (Edvardsson et al., 2012), but in extreme cases floating chronologies have been developed covering over 10,000 years, while standalone chronologies go as far back as to ca. 50 ka BP (Palmer et al., 2006). The reconstruction of past climates can also assist in identifying extreme events such as volcanic eruptions, as these tend to cause periods of extreme cooling (D'arrigo et al., 2001). Furthermore, physical damage caused to a tree can remain as scars inside the tree-trunk, allowing almost exact dating of past events such as fires (Stephens et al., 2003).

Due to its versatility, dendrochronology has been used extensively to both date trees and to assess the relationship between climatic parameters and tree-growth. Dating of trees allows for the reconstruction of past treeline movements (Gamache and Payette, 2005; Aakala et al., 2014), while knowledge of the relationship climate and tree-growth can be used to reconstruct past climate (McCarroll et al., 2013; Fuentes et al., 2018). Besides, the knowledge of how trees react to changing weather pattern can help us predict how treelines are likely to respond to future climate change. Modelling the future extent of tree-limits requires knowledge of the factors currently limiting tree-growth. At most treelines around the world temperature have been identified as the factor responsible for limiting tree-growth (Paulsen and Körner, 2014). However, a warmer climate is not always correlated to treeline migration, indicating that other climatic and non-climatic factors may be responsible for limiting treeline movements (Harsch et al., 2009).

Dendrochronology is hence particularly useful as it allows us to understand the factor limiting the growth of trees at a particular location. Trees in some location may find an increase in temperature to cause additional stress if these climatic trends are combined with reduced precipitation (Farahat and Linderholm, 2018). In addition to measuring the width of growth-rings, analysis of stable carbon, hydrogen and oxygen isotope can provide additional climate proxy data. While this method is significantly more costly and time-consuming, it has the benefit of providing climate proxy data even when tree-ring analysis has failed to provide such information (Loader et al., 2007). The proxy-data obtained by dendrochronology can furthermore be used in growth models capable of estimating the future distribution of trees under various climate change scenarios (Lloyd et al., 2002).

Dendrochronology has proven to be a useful method in studies relating to treeline migration. By determining the approximate year in which a tree established the method could be used to identify movements of the uppermost tree-limit. Through counting of tree-rings, it is possible to map the demographic structures of trees in a forest. If trees become progressively younger at higher elevation or latitude, it is reasonable to assume that the treeline has expanded. By noting at what year each tree established, it also becomes possible to estimate the rate at which the treeline is moving (Elliott and Kipfmueller, 2011).

By reconstructing the climate or using recorded climatic data, it is furthermore possible to identify what climatic parameters appear to be favourable for seedling establishment and survival in an area (Bestic et al., 2005). Tree-rings are particularly useful in the sense that trees can survive for hundreds to over a thousand years, and treeline movements can therefore be reconstructed as far back as the oldest standing tree. Trunks of dead trees are sometimes well preserved, which provides an opportunity to use discs from these trees in combination with cores from live trees to create longer chronologies (Mazepa, 2005). Presence of tree-trunks or fossilised trees above the present-day treeline can provide a good indication of treeline recession (Salzer et al., 2014), which can either be a sign of a change to a less favourable climate, a large disruptive event such as a forest fire, or anthropogenic disturbance.

There are several factors which may prevent the use of dendrochronology when assessing treeline movements. These can be factors such as (I) the lack of annual growth rings in some species, (II) the difficulties associated with drilling in some hardwood species, (III) the remoteness of many treeline sites, (IV) the spatial extent of treelines and (V) the invasive nature associated with the method. We will in the following section briefly discuss these limitations as well as steps that can be used to reduce the influence of these limitations where possible.

Firstly, successful dating of trees relies on the formation of annual growth rings. Annual growth rings form when trees move between phases of dormancy and growth, and hence require seasonal changes triggering this response (Schweingruber, 2012). This is often problematic in tropical climates where seasonality is small, and precipitation signals may dominate over temperature effects in tree-rings. Even in seasonal climatic areas, not all trees form annual growth rings. Some trees may form clear growth rings but are prone to creating false rings, or have lobate growth which can cause growth rings to be absent at certain points of the trunk (Dunwiddie and LaMarche, 1980). Furthermore, not all tree species have been successfully used for cross-dating (Grissino-Mayer, 1993). This means that while the specie may be used for dating if they form clear growth rings, they are not suited for climate reconstructions. Due to the varying suitability of species to dendrochronological studies, it is important to identify the tree-specie at hand to assess its suitability for this method.

Some hardwood tree species of high density, and in particular those with a large circumference, have proven extremely difficult to core manually with hand-held increment borers (Krottenthaler et al., 2015). This issue has driven inventive solutions where electric drills replace the manual turning of the corer (Steenkamp et al., 1999) or where "smart increment borers" have been designed similar to an electric winch (Kagawa and Fujiwara, 2018). Hence, while the hardness of the tree may provide difficulties in drilling and somewhat slow down the process, some methods can be applied to reduce the risk of broken increment borers and slow progress.

Treeline environments are predominantly made up of either high alpine environments or high latitudinal landscapes. While some of these sites are located near human settlements and within easy road access, such as in the European Alps, treelines extend across the vast landscape of northern Canada and Siberia. The remote location and the vast expanses of these sites can provide difficulties in terms of access. Physical mapping of these areas is not only time-consuming but can also become very expensive when a helicopter is sometimes the only mode of transport. Mountain ranges are likely to show more diversity when it comes to microclimates which can either facilitate or limit tree-growth. This is both due to the topographic differences causing steeper temperature gradients as well as a more significant variation in local topography. Hence, treeline migration can be expected to show more diversity over shorter distances compared to flat tundra landscapes. This can question the need for accessing multiple sites to capture overall trends in tundra landscapes of closer proximity. However, these types of studies have indeed shown to be possible (Esper and Schweingruber, 2004; Devi et al., 2008), and favour can be given to locations which have relatively easy access despite their often-remote location (Mamet and Kershaw, 2012).

Dendrochronology is an invasive method as a core is taken from the trunk of the tree. Hence, concerns can arise as to the long- and short-term damage this may cause to trees. While the core extracted is small, and the process is generally considered to have minimal impact on the health of trees (Norton, 1998; Wunder et al., 2013), a few studies have reported significant consequences to the health of trees from coring, sometimes even causing tree-mortality (Tsen et al., 2016). Due to the still somewhat limited knowledge on the impact of tree-coring on the long-term health of trees, Tsen et al. (2016) "caution that the decision to core, or not to core, must be given careful consideration on a case-by-case basis". It can also be considered that trees growing at or near the treeline are already experienceing harsh conditions and perhaps more external stressors than most other trees. Readers considering the use of dendrochronology may further want to consider using the best-practice guide, created both to assess the need for coring and also to reduce any potential consequences coring may have cause to the health of the tree (Tsen et al., 2016).

2.2. Measurement of Tree-Diameter

Another more sparsely used method to estimate tree-age is to measure the circumference of the stem (usually the diameter at breast height at 1.5 m). This method can only be applied where there is a known relationship between the age of a tree and its diameter, which has to be established through dendrochronology (Prabinarana et al., 2017). The method furthermore only works where there is a significant correlation between age and basal diameter or diameter at breast height, which is not always the case. At least some species in specific genera appear to display this correlation, such Rhododendron (Eşen et al., 2004; Prabinarana et al., 2017), Fraxinus (Csontos et al., 2001), and Betula (Yang-jian et al., 2001; Shrestha et al., 2007). While it is easy to see how there could be a relationship between tree size and age where trees are growing under similar conditions, the treeline environment represents a gradual transition zone where species at the treeline are growing at their climatic limit. Therefore, trees found at or near the treeline will often grow more slowly, resulting in trees often become gradually smaller as they approach their climatic threshold (Grace et al., 2002; Jørgensen, 2009). This may be particularly true on mountains where growing conditions change rapidly due to sharp changes in isotherms.

In addition, trees growing under harsh climatic conditions may appear either as dwarf shrubs (Grace et al., 2002), or display a stunted growth form referred to as krummholz (Esper and Schweingruber, 2004). Hence, establishing a relationship between stem diameter and age is likely to be near impossible in areas where the same population is growing under different climatic conditions. It is essential to note that while the correlation between age and tree-diameter has been recognised at a local scale, there is little evidence to assume that there would be global relationships between tree-diameter and age. Therefore, care should be taken when applying this method, as there may be significant variations across different species and sites. As a consequence of these factors, we do not recommend tree-diameter to be used in attempts at determining the age of trees growing in treeline environments. We have therefore decided not to discuss this method in the section on method selection, as other methods are likely to yield far more accurate results in determining treeline migration.

2.3. Repeat Transects

There is a range of studies investigating treeline movements that are based on repeat vegetation surveys along transects. This type of study has been particularly prevalent in the Swedish Scandes where researcher Leif Kullman has studied vegetation changes occurring over time (Kullman, 2000, 2001, 2003, 2005, 2007; Öberg and Kullman, 2012). As treelines tend to shift slowly, capturing changes to their altitudinal or latitudinal position can be very difficult. Hence, detailed vegetation transects performed during the earlier parts of the 20th century, such as those undertaken by Smith (1911) and Kilander (1955), have greatly assisted in detecting changes to treelines in the Swedish Scandes. There are a plethora of past vegetation surveys around the world, some of which dates back to the pre-European settlement of North America. These include the mapping of south-eastern Vancouver Island, Canada, in 1859 ~ 1874 (Bjorkman and Vellend, 2010) or the mapping of northern Wisconsin, US, in the 1860s (White and Mladenoff, 1994). These historical vegetation maps and surveys can be used in comparison with more recent data, to track changes over time.

However, while there is a range of historical descriptions and interpretations available, these are naturally limited in most treeline environments due to their often-remote locations. In the absence of historical data, repeat transects are unlikely to be the preferred method of choice to track changes to treeline positions. High-resolution satellite data is available in most of the world from the past few decades. This data can be used to monitor more recent changes occurring to the position of treelines, meaning anyone interested in monitoring recent changes occurring to tree is likely better off using already available digital data.

2.4. Photography and Remote Sensing

A range of different remote sensing methods has been applied to identify treeline positions, as well as an array of various processing techniques. While field surveys can be used to very accurately map local treeline positions (Rundqvist et al., 2011; Kirdyanov et al., 2012), the extent and remote location of many treelines have made remotely sensed data the primary method for monitoring and mapping many treelines (Sitch et al., 2007; Guay et al., 2014; Ameztegui et al., 2016). Remote sensing is used both as a standalone method and in combination with field surveys and models (Epstein et al., 2012; Coops et al., 2013). There is a range of imagery that can be used to capture treeline positions, including historic and recent photographs from hand-held cameras, aerial photographs, satellite-derived data, and images captured from airborn scanners. The methods used to track and monitor treelines depend on variables such as the spatial extent of the study area, level of detail required, the temporal scale desired for mapping changes in treeline positions, and most importantly, data availability.

One of the best forms of remote sensing when it comes to high-resolution measurements is aerial photography. This method has successfully been used to map canopy cover changes, allowing tree cover changes to be traced more than 100-years back in time (Myers-Smith et al., 2011). Repeat aerial photography methods have been applied extensively around the world. For example, it has been used to map changes to treeline positions in the Catalan Pyrenees (Ameztegui et al., 2016), in the Swiss Alps of Europe (Gehrig-Fasel et al., 2007), as well as in Alaska in the US (Wilmking et al., 2006). The issue can often be to find historical aerial photograph of sufficient resolution, as the lack of colour and shades that often appear in these photographs can make identification of vegetation difficult (Luo and Dai, 2013). Most research utilising aerial photography cover areas of relatively small spatial scales, due to the time and cost associated with capturing larger areas using aircraft. The number of photographs required for aerial photography analysis is mostly dependent on the size of the study site. This can range from hundreds of photographs for areas stretching thousand kilometres (Ameztegui et al., 2016) to only one for areas covering a few hundred meters in size (Wilmking et al., 2006).

Many studies utilise both modern and historic imagery captured using aircraft. Historical aerial photographs have the benefit that they can be used in combination with modern satellite-derived imagery to track changes in treeline positions (Luo and Dai, 2013). Many countries have databases of high-resolution imagery that have been captured throughout time. These photographs are mainly available from the time of the first and second World War. Historical aerial photographs of high quality are however not available for many treeline sites in the world. While most satellite records only stretch a few decades back in time, there are instances where high-quality satellite imagery have been captured by some of the earliest satellites placed in orbit. One of these data sources is declassified spy-satellite imagery, which for example was utilised by Groen et al. (2012) to track treeline changes along the border of Macedonia and Bulgaria using images captured by the United States Hexagon mission in 1976.

A common characteristic of remotely sensed data used to map treeline position is high spatial resolution, as the spatial resolution of the dataset significantly influence the accuracy of the treeline mapping. In order to map changes that are occurring to individual trees, spatial resolutions often need to range from 0.5 to 4 m (Groen et al., 2012; Luo and Dai, 2013; Mathisen et al., 2014). There are several earth-orbiting satellites which are capable at offering data with adequate spatial resolution, including Quickbird (0.6 ~ 2.4 m resolution) (Hofgaard et al., 2013; Luo and Dai, 2013; Mathisen et al., 2014), WorldView (0.5 m resolution) (Mathisen et al., 2014), and Google Earth (1.8 m resolution) (Groen et al., 2012). Some earth-orbiting satellites which provide a lower spatial resolution, but greater temporal coverage include Landsat MSS (60 m resolution) and Landsat TM (30 m resolution) (Hofgaard et al., 2013).

Another option with remotely sensed imagery is to use airborne vegetation scanners. While these offer a high spatial and temporal resolution, they are likely far more expensive than accessing satellite imagery. Regardless, this method provides a relatively high level of mapping accuracy. Airborne laser scanner (ALS) have in combination with process-based forest growth models been able to predict treeline positions within a 50 m altitudinal zone (Coops et al., 2013). ALS can achieve a very high spatial resolution and has the added benefit that it provides enough data points to map the height of individual trees as well as stand densities.

The spatial resolution is likely to significantly influence the level of error associated with accurately mapping the location of treelines. Historical aerial photographs can be used in combination with satellite imagery, dendrochronology and vegetation surveys to improve accuracy and to improve the understanding of the local site conditions (Myers-Smith et al., 2011; Mathisen et al., 2014). As examples of mapping accuracy, field data collected by Groen et al. (2012) indicated an accumulated error of 18 m in the horizontal plane, and 5.5 m in a vertical direction after using the 1.8 m resolution Google Earth data for treeline mapping. As a comparison, the low-resolution data (30 ~ 60 m) used by Hofgaard et al. (2013) had a standard deviation of position error of 100 to 300 m when measuring latitudinal treeline migration. While this level of accuracy may be acceptable when tracking more dramatic long-term changes in treeline positions, it may not be sufficient to identify changes occurring at a smaller temporal scale.

While satellite sourced imagery may, in general, provide better spatial and temporal resolution than most historical aerial photographs, the relatively young age of high-resolution satellite imagery limits the use of the technology in tracking changes back in time. Often satellite imagery cannot be used as a standalone method when mapping changes in treeline positions occurring more than a few decades back in time. However, what they do provide is frequent updates of vegetation changes at relatively high resolution. This allows annual changes to be mapped and correlated to recent climate data which is now provided regularly for most locations on earth.

In summary, the clear limitation in this field of research is the availability of high-quality historic photography. Repeat aerial photography studies are often only feasible for smaller-scale study sites and requires historical photographs which can be georeferenced and accurately interpreted. This means that while current tree lines have a good potential to be mapped using remote sensing technologies, analysing the impact that past climate change has had on treeline positions is more difficult.

3. Considerations for Method Selection

Various aspects will determine the method most suitable to examine treeline movements. These include factors such as the accessibility to the area, the size of the area of interest, and the availability and quality of any type of historical data (either photographs, notes or maps). Perhaps most importantly, method selection will be dependent on the purpose of the study. Dendrochronology is the only method capable of providing information on changes to treeline positions occurring before other reference data such as photographs, or mapping is available. Hence, it is the only reliable method to identify long-term changes to treelines. Furthermore, the method is also useful in that past climates can be correlated to the establishment of trees, meaning the drivers behind treeline movements may be identified. While these changes are usually correlated to a change in the condition of a single variable over time, such as temperature or precipitation (Kharuk et al., 2010; Elliott and Kipfmueller, 2011; Elliott and Petruccelli, 2018), they can sometimes also be correlated to climatic oscillations (Alftine et al., 2003). Also, historic mortality events and the causes of these may potentially also be identified using dendrochronology (Kavanagh, 2000). All of this information can help to predict what may happen to treeline positions under future anthropogenic warming (Wong et al., 2010).

While dendrochronology can provide annual growth data, it is still good to be cautious in trying to determine the exact time of when trees first established at a specific elevation. Slow-growing species, such as those found in harsh growing conditions, can be more difficult to date and determining the exact ages of trees is challenging (Niklasson, 2002). There is also an increased risk for miss-dating trees growing under severe stress conditions as these may not form complete growth rings each year (Wilmking et al., 2012). It is, therefore, more likely for tree populations near limits of their suitable habitat to appear younger than they are. If more precise ages of trees are of importance, it can be worth considering cross-dating using a combination of different age determination methods to improve tree age estimates (Niklasson, 2002; Fraver et al., 2011; Wilmking et al., 2012). Doing so is more time-consuming and therefore also more expensive, and the benefits of using multiple dating methods, therefore, need be evaluated.

The driver behind treeline migration depends on two critical variables; seedling establishment and survival. Dendro-

Table 1. List of the Considerations that Should be Taken into Account When Deciding Upon the Method to Use When Studying Treeline Migrations and Their Applicability to Four of the Most Common Methodologies

Method Considerations	Dendrochronology	Repeat Transect	Repeat Photography and Remote Sensing
Spatial scale	Small (single mountain)	Small (single mountain)	Large (single mountain to larger regions)
Temporal scale	Determined by the oldest tree	Date of first vegetation survey	Date of oldest image or photograph
Access to study site needed	Yes	Yes	No
Requires historic data	No	Yes	Yes
Invasive method	Yes	No	No
Provides climate correlation data	Yes	No	No
Provide date of when treeline migration started	Yes	No	No

Table 2. Advantages and Disadvantages Associated with the Various Methods in Which Treeline Movements Can be Measured and Monitored

	Dendrochronology	Repeat Transect	Photography and Remote Sensing
Advantages	- The coring process is a relatively simple and well-proven technique - The only method which can be used to assess the relationship between treeline migration and climate change - Can provide an almost exact year of when trees established and when migration started - Provides a rate of movement, and how that rate has changed over time Does not require historical data	- Non-invasive - Can provide an indication of how specie composition is changing over time - If done often, it can track seedling establishments and mortality	- Does not require access to local study site - Can track changes over large scale - Relatively quick data collection and processing - Non-invasive method - Depending on data type, the study of various wavelengths can provide additional information such as changes in photosynthesis and start date of ecological processes
Disadvantages	- Time-consuming - Labour intensive, and hence also expensive - Invasive method that may cause physical damage to trees - Not suitable for all species - Requires physical access to study area - Permit may be more difficult to get for this type of research if forest is of high value, due to risk of damage to trees	- Requires historic data - Relies on the accuracy of historic data - Project has to be ongoing for many years - Requires physical access to study area - Depending on frequency it may only give two snapshots in time and time of migration and rate of movement during various periods cannot be established - Time-consuming method if multiple or long transects are created	- Require access to historic data - Can have large errors if data is of poor resolution - Often requires manual interpretation of imagery, and digitizing treeline can be time-consuming and difficult - Shadows and time of day can make it difficult to interpret black and white photographs - Cannot provide knowledge of movements happening before the oldest photograph - May be expensive

chronology can only be used to determine seedling survival and not establishment, as it is impossible to know what seedlings did not survive until adulthood. Hence, if the drivers of treeline migration are of most importance, and there are sufficient time and budget, it may be worth considering repeat vegetation transects. Recording the presence of seedlings may also indicate where future treeline migration is likely to occur (Gaire et al., 2011). While the presence of seedlings above the current treeline does not guarantee an upward migration, the absence of seedlings at higher elevation indicates that the treeline is likely to remain stationary in the near future (Shiyatov et al., 2005; Trant and Hermanutz, 2014).

The lack of seedling at higher elevation can sometimes be a sign that improved climatic conditions may not drive future treeline migration. For example, the limiting factor of the establishment of trees may be linked to other barriers such as lack of shelter (Harsch et al., 2012), high solar radiation (Bader et al., 2007), or where seed production is very episodic and mortality is high (Cuevas, 2002). Frequent vegetation transects are particularly useful in that they may be able to identify factors that limit treeline migration other than changes to temperature and precipitation. For example, theories surrounding the impact of frost during the growing season (Coop and Givnish, 2007), lack of protective snow cover during winter (Kullman, 2000), and also too heavy snow loads (Aakala et al., 2014) on seedling survival can only be confirmed if vegetation surveys are carried out before and after these events. Vegetation transects are also a more suitable form of analysis where tree species have shown limited success with dendrochronological studies. For example, *Eucalyptus pauciflora* (snow gum), which makes up the Australian treeline, is notoriously difficult to date due to missing and false rings (Brookhouse et al., 2008). Repeat vegetation transects may, in these instances, provide more useful at establishing changes to treeline positions over time (Naccarella et al., 2020).

The many benefits associated with dendrochronology and vegetation transects are sometimes overshadowed by both labour intensive and expensive processing associated with fieldwork. In these instances, remotely sensed data could be a way to work around these barriers. There are several cases where remote sensing may prove more useful than field methods as it neither requires access to the study site or sampling permits. In addition, it allows for much greater spatial coverage. For instance, the use of remotely sensed data allows for treeline studies covering mountain ranges (Martazinova et al., 2009) or even whole territories (MacDonald et al., 1998). While most of these high-resolution data are very recently captured, there are instances where high-resolution satellite imagery is available as far back as in the 1970s (Dumais et al., 2014). Regardless, in the world of treeline movements, this can still be considered a relatively short timeframe.

Some areas of the world are fortunate in that high-resolution photographs capturing alpine ecosystems are available either as aerial photographs or as photographs taken by surveyors, national park workers or researchers (Klasner and Fagre, 2002; Mountain Legacy Project, 2017). When photographs are taken at sufficiently large scales, such as those stored by the Mountain Legacy Project in Canada, it is still possible to analyse vegetation changes occurring across a large spatial extent (Mountain Legacy Project, 2017). Furthermore, when draped over digital elevation models, these photographs can be used to not only identify changes in vegetation but also to track the exact change in elevational position of the treeline.

Some of the factors discussed above are outlined in Table 1, where the suitability of various methods is assessed based on a range of considerations that should be taken into account. These considerations were selected as they determine the suitability of a method in a region, and largely determine what type of output data the study will generate. Furthermore, it is important to point out that multiple methods are often used in conjunction to overcome some of the limitations associated with the various approaches.

All of the aforementioned methods come with advantages and disadvantages. Table 2 provides a summary of the various advantages and disadvantages associated with each method, as this can influence the method selection.

4. Conclusion

Treeline movements can be measured and monitored using a range of different methods. All these methods have their advantages and limitations. While no single method can be described as being superior to another for all types of treeline studies, there is little evidence supporting the use of tree diameter relationships to determine the age of trees in a treeline environment. Several factors should be considered when choosing a method for treeline change analysis. The choice also depends on the availability of historical data the site, and the quality that data. Thought should also be given to if the study intends to track changes to vegetation, and if knowledge of the link between climate change and treeline migration is of importance. In addition, one should consider if an invasive method can be justified in the area, and what potential damage it can cause the trees.

For most sites, analysing long-term changes to treeline require the use of dendrochronology. Dendrochronology also offers the most detailed output data and is the only method allowing the climatic drivers of treeline migration to be examined at greater depth. Repeat vegetation transect does, on the other hand, provide more insight as to the causes of seedling mortality, which can help identify limiting factors of treeline migration. Future research into the use of drones to monitor treeline migration can provide a valuable addition to vegetation transects, as these may be used to quickly scan vegetation changes at extremely high-resolution, covering location which may be otherwise difficult to access. While these types of studies may not be able to provide information on past movements, they could offer significant assistance in speeding up the fieldwork process.

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