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Morpho-physiological Effects of Drought on Medicinal Plants and the Potential Use of Remote Sensing - A Review

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Abstract

This review addresses the growth and development of medicinal plants under arid land conditions and the potential use of remote sensing technologies to map their distribution, as well as morphological and physiological responses in Arid lands. Plant morpho-physiological variables including, chlorophyll content, and gas exchange (photosynthesis, transpiration, vapor pressure, and stomatal conductance) are linked to plant water status. Multispectral and hyperspectral remote sensing techniques are promising for detecting morphological physiological changes. Vegetation indices derived from hyperspectral and multispectral imagery makes it possible to assess medicinal plants' health through successful detection of the ground plant physiological variables and canopy cover including chlorophyll, canopy density, gas exchange (red, 600-700 nm, near-infrared spectrum, 700-1100 nm) as well as water status (shortwave infrared, 1300-2500 nm). Surface reflectance data within the shortwave infrared bands (water bands) revealed significant differences between well-watered and drought-stressed plants. However, the moderate spatial resolution (Sentinel-2: 20 m, Landsat: 30 m) for the space-born free sensors and the need for a cloud-free sky could be limitations. Overall, vegetation indices derived from remotely sensed data are a useful approach for estimating the physiology of plants (medicinal plants) especially those under drought stress.

Keywords: Medicinal Plants, Drought Stress, Water Status, Hyperspectral, Multispectral, Vegetation Index.

1. Introduction

Climate change is one of the major problems facing the world because it is foretelling climate patterns changes and a higher frequency of risky weather events. In recent years, the frequency and severity of droughts in the Mediterranean region have increased due to global warming (IPCC, 2013; Trenberth et al., 2014). Generally, climate change has a potential impact on agriculture, coastal areas, biodiversity, urban systems, society, water, and health sectors (FAO, 2008). In the agricultural sector, climate-change-related risks are represented by higher temperatures, rainfall decreases, the shift in the rainy season and seasonal alterations, heatwaves, and extreme events especially heavy rainfall and droughts (WB, 2021). Drought is a disastrous natural phenomenon that has negative impacts on plants and especially under the changing climate, it becomes more frequent and severe (Seneviratne et al., 2012). Drought has destructive effects on socioeconomic, plants, and the environment because it leads to insufficient precipitation, high evapotranspiration, and over-exploitation of water resources (Yurekli and Kurunc, 2004; Bhuiyan et al., 2006; García-Caparrós et al., 2019). Drought effects can be classified as direct and indirect (Van Lanen and Peters, 2000). Direct impacts of drought are the results of interactions among water deficiencies and environmental, and socio-economical components while indirect are a secondary result of water deficiency and are often occurred far away from the drought-impacted region (UNDRR, 2021).

Generally, drought can be categorized into three basic types in terms of measuring drought as a physical phenomenon; meteorological, agricultural, or hydrological drought (Wilhite and Glantz, 1985). Meteorological drought is a prolonged abnormal dryness period (compared to normal average precipitation), agricultural drought links meteorological variables (e.g., precipitation) to agricultural impacts such as soil water deficits while hydrological drought is associated with the influence of rainfall periods on the surface or groundwater supply (NDMC, 2021). In arid and semi-arid land, functional landscapes and their associated vegetation are ultimately dependent on water availability, which significantly affect vegetation distribution (Tardieu et al., 2018). Drought stress in plants (e.g., Thymus citriodorus) normally plants moisture content (dehydration) followed by a reduction in the metabolism process and photosynthesis and consequently plants death (Tátrai et al., 2016). However, the ability of plants to survive under stressed conditions depends on plant species, growth stage, duration, and the intensity of water deficit (Blum, 2017). Plant tolerance to abiotic stress such as water stress is unpredictable because of the complicated interactions between stress factors and plant molecular, biochemical, and physiological components associated with growth and development processes (Razmjoo et al., 2008).

Medicinal plants are the major sources of numerous valuable chemicals and/or drugs worldwide. According to the International Union for Conservation of Nature (IUCN)

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and the World Wildlife Fund (WWF), about 50,000–80,000 flowering plants are used because of their medicinal values. In Europe, over 1300 medicinal plants are used, especially those from the wild sources which account for 90% of the total medicinal plants (Hao, 2019). Jordan is home to an abundance of flora and fauna, about 2978 plant species belonging to 120 families and 719 genera are recorded in Jordan (Abdelhalim et al., 2017). In addition, 20% of the total flora species in Jordan are classified as medicinal plants (Abdelhalim et al., 2017). High demand for medicinal plants coupled with unpredictable environmental stressors such as low rainfall has led to a significant reduction in their abundance worldwide. Cultural practices such as planting method and date, fertilizer application, irrigation regimes, and harvesting should be optimized to increase the growth and productivity of medicinal plants (Tanga et al., 2018). Efforts to conserve wildlife flora including medicinal plants have been observed recently including research studies focused on the growth (e.g soilless culture), physiology, production (yield, phenolic compounds, and oil content), and conservation of those plants (Al-Karaki and Othman 2009; Leskovar and Othman, 2016; Sharma et al., 2020).

Management and monitoring of wild plants including medicinal ones require frequent and consistent assessment of the canopy status and health over time. The main health indicators are morphology and physiological variables including chlorophyll contents, gas exchange [photosynthesis (Pn), transpiration (E), vapor pressure deficit (VPD), and stomatal conductance (gs)] as well as plant development and yield (Tahat et al., 2020). These morpho-physiological variables can provide accurate information about the plant carbon assimilation rate, leaf water level (Othman et al., 2014a; Tadros et al., 2021), plant nutrition, fruit quality, and consequently their health (Al-Ajlouni et al., 2017; A'saf et al., 2020; Ayad et al., 2018; Alsmirat et al. 2018; Leskovar and Othman, 2018, 2021; Tahat et al., 2020). However, these methods of assessment are time-consuming, labor intensive, and expensive. In addition, the distribution of some wildlife flora could be not accessible. Another possible alternative to assess plant health is through remote sensing techniques (Al-Kofahi et al., 2019; Othman et al., 2014b, 2021; Tadros et al., 2020). Remote sensing has potentially assessed chlorophyll content (Othman et al., 2019), canopy density (Othman and St. Hilaire, 2021; Tadros et al., 2020), gas exchange and water status (Othman et al., 2014b, 2015), and geographic distribution (Al-Bakri et al., 2011). Remotely sensed data are providing an upscale view of the land and a spatiotemporal context to measure drought impacts (Hazaymeh and Hassan, 2017). In addition, vegetation indices derived from space-borne sensors (e.g., Landsat and MODIS) such as Normalized Difference Vegetation Index (NDVI) and the Vegetation Condition Index (VCI) have been successfully linked to chlorophyll content and water content in the plants (Rousta et al., 2020). In this review, we evaluated the usefulness of using the remote sensing approach as an alternative for evaluating medicinal plants' morpho-physiological responses under drought conditions.

2. Evaluation of Eco-physiological Parameters of Medicinal Plants

In the developing world, local communities depend on traditional medicine for primary health care (Jeelani et al. 2018). In addition, developed countries heavily use medicinal plants for their pharmaceutical products (Chapman and Chomchalow, 2005). Medicinal plants have several phenolic and antioxidant compounds which used to support human health and cure some diseases. In Jordan, several medicinal plant species are native to Eastern and Northern rangelands (Badia) (Oran and Al-Eisawi, 2015). More than 49 plant families and 120 plant species found in Jordan are used by neighborhood people for medical purposes (Atta and Alkofahi, 1998). However, uncontrolled grazing and frequent drought periods in the last decade reduced their numbers (Oran and Al-Eisawi, 2015). Therefore, research studies that focus on improving the tolerance of the medicinal plant to harsh conditions as well as controlling grazing intensity are essential for the potential sustainability of those plants.

Abiotic, and biotic (soil microorganisms) factors can significantly affect medicinal plant metabolite biosynthesis. Abiotic stresses such as temperature extremes and water stress can negatively affect the physiology and chemical composition of plants, which as a result induce abnormalities in medicinal plant metabolic processes such as growth, photosynthesis performance, and yield (Zaid et al., 2021). Optimal environmental conditions tend to increase medicinal plant biomass rather than synthesizing secondary metabolites (Pavarini et al., 2012). Postharvest processing can also lead to an irreversible quality loss of medicinal plants (Tanga et al., 2018). Therefore, finding proper management practices to guarantee high plant growth, productivity and quality are critical for the medicinal plants industry. In this context, management practices including irrigation, fertilization, and pest control required frequent assessment and evaluation during the growing season to sustain plant health and productivity. To assess the growth performance in response to those cultural practices (irrigation, fertilization, pest management) several plant-base and soil-base measurements have been recommended including water status (e.g. midday stem water potential (Ψsmd), relative water content) and chlorophyll content (Othman et al., 2014b, 2015).

Plant-based measurements such as midday stem water potential, relative water content, gas exchange (Pn, gs, E, VPD, respectively), and leaf pigments are viable approaches to assess the physiology of plants which depict their health status (Jones, 2004; Khasawneh et al., 2021; Leskovar and Othman, 2019; Othman and Leskovar, 2018, 2019). This is because many features of the tree's physiology react immediately to changes in tree tissues including water status (Jones, 2004). For example, Othman et al., (2014a) reported that under deficit water stress, Ψsmd and gas exchange were significantly lower and resulted in lower growth rate and yield compared to non-water-stressed plants. Although total soluble sugars and proline concentration in chamomile (Matricaria chamomilla L.) was similar across water deficit regimes, the total chlorophyll concentration was significantly reduced in water deficit plants (55% of field capacity) compared to control (100% field capacity) (Pirzad et al., 2011).

Chlorophyll and carotenoids (carotenes and xanthophyll) are the major pigments of green leaves (Gitelson et al., 2002; Li et al., 2018). Pigment concentration inside the leaves potentially reflects the physiological performance of plants (Gamon and Surfus, 1999; Blackburn, 2007). This is because leaf pigments (chlorophyll, and anthocyanin) level in the leaves could act as a photoprotective mechanism that mitigates water deficit impact (Gamon and Surfus, 1999; Gori et al., 2021). Chlorophyll fluorescence (Fv/Fm) is a leaf-level physiological measurement that is used to study the performance of chlorophyll pigments under stress such as drought (Guidi et al., 2019). The decrease in Fv/Fm value is an indicator of low performance of photosynthetic pigments specifically, photosystem II (PSII) efficiency (Guidi et al., 2019). However, chlorophyll fluorescence measurements (re-emitted light from PSII) can interfere with the sunlight and thus many early systems had to be used in darkness and/or highly controlled light environments and it remains stable under mild and moderate drought stress and shows a significant decline only under severe drought conditions (Othman et al., 2014a). Gas exchange also is used in assessing plant performance including those studies focusing on plant growth and productivity as well as fruit quality (Leskovar and Othman, 2021; Kasaweneh et al., 2021). Gas exchange variables (Pn, gs, and E) normally decreased in parallel with increased stressors such as water deficit and nutrient deficiency (Ayad et al., 2018).

Water status is one of the most important factors limiting medicinal plant performance, especially those grown in an arid environment (Khorasaninejad et al., 2010; Pirzad et al., 2011). For example, drought stress significantly reduced the growth rate, essential oil, and yield of mint (Mentha piperita L.) compared to those grown under 100% field capacity (Khorasaninejad et al., 2010). Low soil moisture reduces stomatal conductance, total lipid content, photosynthetic capacity, chlorophyll content, transpiration, and the total dry matter (Guerfel et al., 2008; Grams et al., 2007; He et al., 2007; Warren et al., 2007; Damour et al., 2009; Arunyanark et al., 2008). At moderate drought, Pn decreased slightly because of the reduction of stomatal aperture that interacts with CO_2 diffusion as well as the intercellular CO_2 (Ci) inside the stomata; stomatal limitation effect (Cifre et al., 2005). However, at severe water deficits, Pn further declines and Ci increases indicating that non-stomatal limitations become significant (Tezara et al., 1999). Othman et al (2014a) screened leaf-level physiological changes that occurred during cyclic irrigation to determine parameters that best-represented changes in plants; the physiological variables included midday stem water potential (Ψ_{smd}), relative water content (RWC), the osmotic potential at full turgor (π), leaf area ratio (LAR), gas exchange (Pn, gs, and E) chlorophyll content and fluorescence (Fv/Fm). They found that Ψ_{smd} was the best leaf-level physiological response to detect moisture status in plants. Although the study was on woody trees, a similar trend was found in medicinal plants (Kalamartzis et al., 2020). For example, water deficit stress increased leaf temperature, Ψ_{smd}, gas exchange parameters, and dry herb yield of Ocimum basilicum (Kalamartzis et al., 2020).

Although physiological measurements are a reliable source to assess plant health, the amount of time involved in data collection and the difficulties of automation of those instruments could be critical limitations to using ground physiological measurement to upscale the response to a large scale (Jones, 2004; Qarallah et al., 2021). In addition, physiological variables are at the leaf-level scale, which might be not representative of the whole tree's status (Othman et al., 2021). For example, high-performance liquid chromatography is usually used to measure pigment concentration inside the leaf, but the extraordinary cost and extraction time, along with the necessity of leaf destruction, limit its usage (Gamon and Surfus, 1999). Midday stem water potential equipment (pressure chamber) is not automated which requires the person to be onsite, requires leaf destruction, and might not be safe because of pressurized gas inside the instrument. Given that leaf-level physiological measurement is not easy, to upscale to a large scale, finding another alternative to estimate plant health is a critical issue for the plants in general and the medicinal plants' community specifically.

3. The role of remote sensing in assessing medicinal plants under drought conditions

The remote sensing approach involves the acquisition of information about an object without being in direct contact with it (Jensen, 2005). This technique enables researchers to collect information about plants in rugged topography places that are not accessible for plant-based measurements (Othman, 2014). Remote sensing is a promising approach for detecting and predicting plant morphological and physiological traits such as chlorophyll content, canopy density, and water status (Othman et al., 2014b; Santos et al., 2008). These techniques can detect, predict, and scale up leaf-level physiological responses to large areas without destroying leaves or plants (Ormeci et al., 2009). Multi-spectral satellite imagery can provide information covering large areas, while aerial photography with unmanned aerial vehicles (UAV) allows us to collect comprehensive biometric information from sites under investigation (Table 1). UAV created orthophoto with high quality that allowed confidently interprets the medicinal plants' communities during different growth stages including flowering (Fadeev et al., 2019). The combined use of multispectral aerial and satellite imagery and the high spatial resolution of UAV photography scaled up the vegetation (e.g., medicinal plants) in significant areas and accelerated the work in large areas (Fadeev et al., 2019; Qarallah et al., 2021). The age of an endangered medicinal and aromatic plant species Valeriana jatamansi was successfully identified using field hyperspectral remote sensing and machine learning techniques. This combined approach provides a scientific way for harvesting this plant at its optimum age avoiding its wastage (Kandpal et al., 2021). A multilevel monitoring system including spaceborne (Landsat), aerial remote sensing, and field measurement was conducted to monitor the medicinal plant (Rheum tanguticum) resource in Sichuan Province, China (Xie et al., 2014). They found that only the R. tanguticum with canopy coverages of more than 1 m^2 could be detected from the aerial of 10 cm resolution. Landsat alone has limited capability of detecting the scattered R. tanguticum plants.

Table 1. Satellite and field sensor spectral, spatial, and radiometric data and their application in vegetation studies.

Platform	Sensor	Revisit time (day)	Spatial Resolution (m)	Variable	Example
Sentinel-2A	MSI	5	10 -20	Leaf area, productivity	Cerasoli et al., (2018).
Landsat 8	OLI	16	30	Leaf area, chlorophyll, photosynthesis, water stress.	Othman et al., (2014b, 2018, 2020, 2021); Tadros et al., (2020), Sawalhah et al., (2018; 2021).
NOAA-15	AVHRR/3	1	1090	Leaf area index	Liu et al., (2012)
TERRA / AQUA	MODIS	1 – 2	250-1000	Equivalent water thickness, leaf area index, chlorophyll-*a*, fraction of photosynthetically active radiation	Cheng et al., (2013), Liu et al., (2012), Moses et al., (2009),Qu et al., (2014), Yang et al., (2006).
SPOT-5	HRS	27	5	Leaf area index and soil moisture.	Soudani et al., (2006), Gouveia et al., (2009).
	HRG	27	10		
	VEGETATION	1	165		
IKONOS-2	OSA	11- 14	4	Leaf area index, and chlorophyll-*a*.	Soudani et al., (2006), Ormeci et al., (2009).
ASD Fieldspec Pro Full Range Spectroradiometer	-		≈ 1.0 m^2 at 1m nadir view (25° field-of-view)	Relative water content, chlorophyll florescent, photosynthesis, and leaf water content.	Matsushita et al., (2010), Othman et al., (2015, 2020).

The water content of plants is an essential variable for the growth and productivity of medicinal plants. The water status of plants can be monitored with surface reflectance data. Generally, canopy reflectance at near infrared (NIR, 700 – 1200 nm) is higher than at shortwave infrared (SWIR; 1300 – 2500 nm) (Figure 1). This is because leaf water status has a dominant influence in the SWIR wavelengths by strongly absorbing spectral reflectance in this spectra region (Pu et al., 2003; Eitel et al., 2006). Water status (drought) indices are commonly used to detect the potential risk of occurrence and severity of drought, and to study spatial–temporal reasoning. Remotely-sensing indices such as water band index (WBI) and band ratio (NIR/SWIR) response to water status in the plant by detecting the canopy surface reflectance in the “water bands” spectrum (1200 to 2500 nm spectral range) during drought and recovery cycles (Claudio et al., 2006; Othman et al., 2014b). Under drought conditions, the spectral reflectance in the SWIR region (water absorption region) increased and change the vegetation values of indices that rely on these bands (Eitel et al., 2006). Up to now, several remote sensing methods have been established and used for agricultural drought monitoring such as vegetation indices, band ratio and empirical remote sensing algorithms (Ligi et al., 2017; Zargar et al., 2011). These methods showed the potential results in terms of detecting drought conditions in plants (Faragó et al., 1993; Zargar et al., 2011).

The use of remote sensing techniques to monitor drought and assess its influence has been widely adopted recently (Manesh et al., 2019). It is possible to observe the intensity of plant water stress and to detect the damage in crop areas using various agricultural drought indices (Ryu et al., 2019). This directly affects agricultural production (agricultural drought), which is most often visible in the physiological condition of plants and can be assessed from ground or satellite sensors (Wu et al., 2015; Othman et al., 2015, 2021). Using these land-surface properties, numerous satellite-based water stress indices (drought) have been developed for effective monitoring (AghaKouchak et al., 2015). However, the correlations among this vegetation are not always accurate because the definitions of indices are conceptually different based on the indicated drought phenomenon and the time scale for observing the progress (Zhang et al., 2017). In addition, the parameters used in the calculation of each index differ according to the meteorological, agricultural, and hydrological drought concepts (Anggraini et al., 2016). For example, while meteorological drought considers only atmospheric dry conditions, agricultural, and hydrological droughts are highly related to land conditions. In Iași region/Romania, the land of several aromatic and medicinal plants including Verbena Officinalis, Macarof and Stătescu (2017) found that Normalized Vegetation Supply Water Index (NVSWI) derived from Landsat 8 Operational Land Imager (OLI) were able to detect drought stress. Karnaris and Asimopoulos (2020) reviewed the use of the unmanned aerial vehicle for detecting aromatic plant growth change and response to harsh micro-climate in Greece. They find that UAV were able to detect vegetation cover changes (NDVI). However, more studies and vegetation indices should be developed for the Western Macedonia region to successfully detect the response of the aromatic-medicinal plants to harsh conditions (cold-dry).

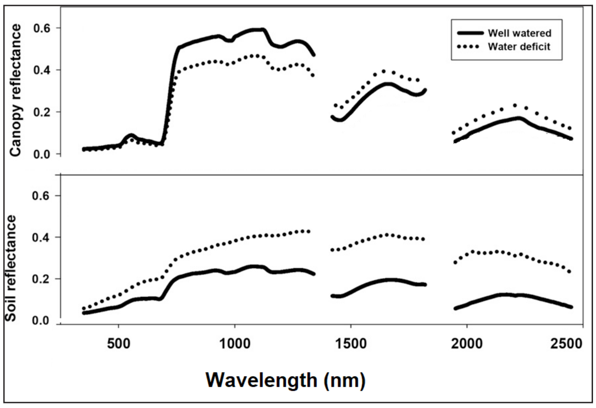

Figure 1. Canopy and soil surface reflectance under well-water and drought stress conditions for woody plants. Source: Canopy reflectance data were from Bayat et al. (2016) and soil data were from Othman (2014).

Leaf pigments including chlorophyll and carotenoids are essential for several plant processes such as carbon assimilation. Chlorophyll is a green pigment found in chloroplast and present in green algae and terrestrial plants in two forms, chlorophyll, a and b. This pigment absorbs light mainly in the red (650 – 700 nm) and the blue (400 – 500 nm) and reflects the green light (~550 nm) (Jones and Vaughan, 2010). Remotely sensed data of leaf pigments especially chlorophyll can predict the leaf's physiological status and consequently the plants' health (Gamon and Surfus, 1999).Surface reflectance at 510, 550, 700 and 750 nm significantly correlated ($R^2 > 0.75$) with the total carotenoids in the leaves (Gitelson et al., 2002). Othman et al. (2018) found that multispectral data from Landsat ETM+ are a reliable source to detect chlorophyll content in the plant. In addition, Ormeci et al. (2009) concluded that IKONOS data are a reliable source for detecting chlorophyll-a in large areas even if the in-situ measurements are limited. At drought stress, excess light energy migrates from the chlorophyll molecules to the xanthophyll cycle to protect the system from damage (Grace et al., 2007). This energy causes a shift in the xanthophyll cycle, at which point violaxanthin is converted into zeaxanthin causing excess energy dissipation (Naumann et al., 2009). The hyperspectral vegetation index, and photochemical reflectance index (PRI) successfully measured the efficiency of the xanthophyll (Naumann et al., 2009).Suàrez et al. (2008) found that canopy-PRI derived from Airborne Hyperspectral Scanner (AHS) sensor was able to detect the physiological responses (xanthophyll pigment cycle, stomatal conductance, and stem water potential) of plants (Suàrez et al., 2008). In addition, Thenot et al. (2002) revealed that PRI could be a non-destructive, cost-effective method for detecting water stress in Chenopodium quinoa. Considering the previous studies that showed a significant relationship between remotely sensed data and leaf pigments, especially chlorophyll (content and fluorescence), we believe that remote sensing data are a reliable source to assess plant chlorophyll and hence plant health.

Precision agriculture of woody and herbaceous crops including medicinal plants requires a piece of accurate information about the canopy, specifically coverage percentage. Leaf area index (LAI) is an essential variable that is used to estimate vegetation cover and productivity and as an input to water and energy budgets and ecosystem process models (Butson et al., 2002; Fernandes et al., 2004). When LAI strongly correlates with remotely sensed vegetation indices, these indices can be used to scale up those variables over large regions (Treitz et al., 2010).Othman and St. Hilaire (2021) found that three vegetation indices derived from Landsat ETM+ were able to estimate LAI correctly. The vegetation indices were normalized difference infrared Index-band 5 (NDII5), enhanced vegetation index (EVI), and green normalized difference vegetation index (GNDVI). In addition, Liu et al. (2012) concluded that vegetation indices from Landsat TM/ETM$^+$ including normalized difference vegetation index (NDVI), the optimized soil adjusted vegetation index (OSAVI), the two bands enhanced vegetation index (EVI2) and the modified triangular vegetation index (MTVI2) can be used to derive LAI map for seasonal crop growth monitoring. Considering the finding of previous studies, the use of datasets from high-resolution aerial sensors and moderate satellites images are holding promises for detecting medicinal plants' health status by estimating canopy cover and chlorophyll content (red, 600-700 nm; near-infrared spectrum, 700-1100 nm) as well as water status (shortwave infrared, 1300-2500 nm).

4. Remote sensing limitations

The current limitations for using remotely sensed data are mainly due to restricted spectral range, coarse spatial resolution (more than 30 m), low temporal resolution (revisit time) as well as inadequate repeat coverage during the growing season (Moran et al., 1997). In addition, image pre-processing of aircraft- and satellite-based images required specialized software and workers. For example, satellite sensor data requires atmospheric and geometric correction before utilization using special software such as ENVI and ERDAS IMAGINE (Othman et al., 2018; Sawalhah et al., 2018, 2021). In addition, the acquisition of cloud-free space-born images (e.g., MODIS, Landsat) is one of the biggest challenges (Whitcraft et al., 2015). During the satellite overpass, the area should be cloud-free to guarantee meaningful images. Therefore, this tool could be inefficient during winter and early spring; the time when clouds cover percentage is extremely high. Although multispectral remotely sensed data such as Landsat series and Sentinel-2, hyperspectral remote sensing equipment is extremely expensive. In terms of physiological assessment, data from several remote sensing studies could show a pattern of difficulties in predicting or detecting the plant response. For example, when plants are under moderate water stress the difference in reflectance is quite narrow. As a result, the plant could be exposed to water stress through the surface reflectance is almost similar. At the field scale, both high spatial and high temporal data are required due to the small size of agricultural fields and the quick changes in plants through the growing season (Becker-Reshef et al., 2010; Rocha et al., 2012; Atzberger, 2013). For example, moderate spatial resolution data (i.e., 30 m) is essential for studying plant responses at a field scale (Roy et al., 2014), and high temporal resolution data (i.e., weekly) is obligatory for monitoring quick changes during the growing season (Zhang et al., 2003; Kovalskyy et al., 2012). These variations, in some cases, may reflect specific agricultural difficulties such as drought (McVicar and Jupp, 1998). Generally, if the spatial resolution is high enough (e.g., less, or equal to 30 m), then it is reasonably easy to compare with ground-based measurements. When the coarse spatial resolution is used, a combined airborne and space-borne remote sensing datasets might be used for favorable accuracy (Hazaymeh and Hassan, 2016).

5. Conclusions

Plant-based measurements including midday stem water potential, relative water content, gas exchange (Pn, gs, E and VPD), and leaf pigments (chlorophyll and carotenoids) are the best physiological measurements to assess the response of plants to environmental stresses including those planted for medicinal usage. However, those measurements are time consuming and expensive. Remotely sensed data from hyperspectral and multispectral sensors make it possible to assess medicinal plant physiology through successful detection of the ground leaf and canopy physiological variables including water status, chlorophyll, and LAI. Shortwave infrared indices such as vegetation water stress index are useful for estimating medicinal plant water status especially when ground physiological measurements (e.g., midday stem water potential) are limited. However, those remotely sensed indices can markedly predict water levels in medicinal plants under severe water stress conditions. Surface reflectance vegetation indices can be used in estimating water status in vegetation including medicinal plants when rainfall is the only source of water and when plants are exposed to severe water stress. Under commercial production of medicinal plants, the use of those indices could be not accurate because growers will not allow them to fully dry, exposing plants to severe water stress. Despite being inefficient occasionally, remote sensing sensors are a viable and accurate tool; and hold promise for assessing vegetation health including medicinal plants.

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