Societies, such as heroin-related overdose deaths (Ciccarone et al., 1997), are globally widespread, causing severe problems to individuals and communities. Heroin is well known as a major drug of abuse with a specific and illegal trade. Heroin is frequently processed chemically to produce heroin for the illegal drug trade. Morphine, however, is also an opiate alkaloid that is known for its analgesic properties, and codeine is widely prescribed as an analgesic and cough suppressant. Morphine is one of the most effective treatments for severe pain, and codeine is widely prescribed as an analgesic and cough suppressant. Morphine, however, is also an opiate alkaloid that is frequently processed chemically to produce heroin for the illegal drug trade. Heroin is known to be a major drug of abuse with a worldwide trade, which can cause severe problems to individuals and societies, such as heroin-related overdose deaths (Ciccarone et al., 2009) and involvement of crime (Gibson et al., 2005).

In 2008, approximately 99% of the world’s potential opium production calculated based on the opium poppy cultivation is concentrated in Afghanistan and Myanmar, the remainder being mainly distributed in Pakistan, Lao PDR, Colombia (UNODC, 2009). Knowing where poppy is cultivated and how much opium can be produced is important for governments and the international communities to understand and tackle the illegal drug trade. Opium yield and poppy cultivation acreage form the basis for estimating potential opium production. Opium is processed to produce morphine and heroin (UNODC, 2009). Therefore, information on opium production may provide a starting point for analyzing illegal drug trades and implementing drug fighting policies.

Remote sensing offers a potential way of monitoring large area for opium poppy cultivation (Chuinsiri et al., 1997). The United Nations Office on Drugs and Crime (UNODC) conducts an annual monitoring in major opium poppy cultivation countries using sampling based methods with high resolution remote sensing data (UNODC, 2007, 2008, 2009). Similarly, under a bilateral agreement between Chinese and Myanmar governments, the Chinese National Narcotics Control Commission (CNNCC) conducts such an annual monitoring in Myanmar using a full-coverage method using remote sensing observations (CNNCC, 2008; Tian et al., 2011). Important problems are to get opium yield information in an efficient way, and to combine such information with the estimated cultivation acreage for potential opium production. UNODC adopts a random sampling method to select field plots. It collects opium...
The study explores the feasibility of assessing opium yield using remote sensing. Combined with the opium poppy cultivation acreage, this should lead to a full assessment of opium production at a regional scale. An efficient remote sensing-based method would allow a rapid collection of opium yield information without interference of personal harvesting skills, leading to more comprehensive and precise opium production information.

The objective of this study is to find an effective biophysical indicator that can be related both to opium yield estimation and remote sensing measurements. The study uses data from three years' experiments that have been conducted with support of the CNNCC in an official farm in North-Western China.

2. Study area

The study area is selected in an official farm in northwestern China's Gansu province that is located in a dry and hot valley. In this arid environment, the crops receive abundant sunlight and an average precipitation of 173.3 mm per year, thus resulting in weather conditions that are highly suitable for poppy growth. The three irrigation systems use water from reservoir during the growth period of poppy. In the study site, poppy seeds are always sown in late March in well cultivated fields. The seeds sprout into small seedling about one month later. Flowering occurs in late June, with capsules forming at the beginning of July. The flower is white and each plant contains a single capsule with a diameter between 4 and 6 cm. During harvest time around mid-July, the opium is harvested by collecting the black gum formed from the white latex released by lacerating the immature capsules.

3. Data and method

3.1. Field campaigns

Field measurements are conducted periodically in 2007, 2008, and 2009 (Table 1). Every year, sample sites (10 m x 10 m) within the study area are selected based on growth condition of opium poppy (Fig. 1). At each site, opium yield and plant parameters including leaf area index (LAI) and plant height (H) in different growth periods of opium poppy are measured. Within each site, five plots are established, with one plot at the center of the site and the other four plots located at a distance of 2 m from the nearest two sides of the central site (Fig. 2). During the experiment, the pheno-logy of poppy is divided into four periods (Fig. 1): T1: seedling, T2: before flowering, T3: flowering and T4: harvesting. The average plant height increases from 20 cm to 130 cm during the successive periods (Table 1).

Opium yield data collection consists of two steps. At the first step, the planting density is determined by counting the number of individual plant per one square meter. At each site, three plots...
are randomly selected, the number of plants is counted and the average serves as the planting density of this site. At the second step, 20 capsules representative of the average production level are selected to collect opium gum at each site. These capsules are carefully incised horizontally around their circumference using a single knife. The incision is made sufficiently deep to incise the lactiferous ducts, but not to penetrate the endocarp, which may result in the death of the capsule. White latex exudes from the incisions and rapidly darkens to a blackish color once exposure to air. The darkened gum is collected within a labeled container for each site and exposed in the sunshine. Each capsule is incised seven times during the next several days. When the opium gum is dried, the weight of the opium from 20 capsules is determined using an electronic balance of a 0.1 g precision. Then the average of the opium from 20 capsules is representative for the opium produced by a single capsule. The opium yield (g m\(^{-2}\)) is then determined by multiplying the planting density and the average opium weight of one capsule.

LAI, defined as one-half the total green leaf area per unit ground area for vegetation canopies (Chen and Black, 1992), is a key parameter controlling many biological and physical processes associated with vegetation (Johnson et al., 2003). In this study, LAI is measured using LAI 2000 plant canopy analyzer (LI-COR, Inc., Nebraska, USA), being widely used optical instruments for \textit{in situ} LAI estimation. At each site, diffuse radiation above the poppy canopy is measured as a reference, followed by measurements at the five plots below the poppy canopy. Post-processing of the measurements is accomplished using the LAI-2000 analysis software provided by LICOR (FV2000.exe).

Plant height is measured using a steel measuring tape from the ground to the top of the plant. Ten plants representative of the average height are selected at each site, and their average height serves as the plant height of this site.

3.2. Data analysis

To find an impact or suitable factor for estimating opium yield, scatter plots between opium yield values and plant parameters measured in different growth periods of opium poppy are drawn. A linear regression analysis between opium yield and plant height (\(H\)), LAI and the multiplying value of plant height and LAI (\(H \times \text{LAI}\)) is applied to quantify and explain the relationships with opium yield.
4. Results

4.1. Relationship between opium yield and plant height

No general trend can be observed between opium yield and plant height in all the four growth periods in this study (Fig. 3). Apparently, plant height has little relation to the growth condition of opium poppy and hence to the production of opium gum. Therefore, plant height is not a decisive factor for opium yield and not a suitable indicator for opium yield estimation.

4.2. Relationship between opium yield and LAI

A significant correlation between opium yield and LAI has been observed in the periods in T2, T3 and T4. This relation was absent in period T1 (Fig. 4). In the seedling period T1, the poppy plant has still a long time to develop until harvesting, which also is not the key period of opium gum forming. For that reason, the LAI does not reflect the opium yield information in this period (Fig. 4a). The relationship between LAI and opium yield is more apparent in periods T2, T3 and T4, showing an increase in opium production with the LAI (Fig. 4b–d). A high LAI is therefore an indication of good growth conditions, leading to higher opium yield. During T2, the correlation between opium yield and LAI becomes apparent (Opium Yield = 1.6 × LAI + 0.302, $R^2 = 0.62$) (Fig. 4b). During T3 (Opium Yield = 0.7 × LAI + 2.102, $R^2 = 0.8269$) and T4 (Opium Yield = 1.0 × LAI + 0.856, $R^2 = 0.8620$), the correlation between opium yield and LAI increases (Fig. 4c and d). It can be concluded that the LAI during flowering and harvesting is a good candidate for an indicator and can be used for opium yield estimation.

4.3. Relationship between opium yield and $H \times LAI$

Similar to plant height and LAI, the product $H \times LAI$ only shows a weak correlation with opium yield during T1 (Fig. 5a). However, the correlation increases during T2, T3 and T4 (Fig. 5b–d). Opium yield increases with increasing $H \times LAI$ values. Hence, a higher $H \times LAI$ value may indicate better growth conditions and a higher opium gum production. In T2 the $R^2$ between opium yield and $H \times LAI$ is a 0.03 higher than between opium yield and LAI, in T3 it is 0.01 higher, whereas in T4 it is 0.06 lower (Fig. 5b–d). Clearly, $H \times LAI$ is another suitable candidate for an indicator for opium yield estimation.

The results presented so far show that LAI and $H \times LAI$ are two suitable candidates during the flowering and harvesting stages of opium poppy for estimating opium yield. Because of the $R^2$ values and because of difficulty in measuring plant height using remote sensing, the LAI is a better and effective indicator. The LAI is therefore selected as the biophysical indicator for opium yield estimation.

5. Discussion

LAI is a canopy structure variable which is a key parameter controlling many biological and physical processes associated with vegetation (Tang et al., 2007). LAI is also a synthetically plant parameter that can indicate crop growth conditions in a quantitative way (Yao et al., 2008). This study shows that the LAI observed during the flowering and harvesting periods of opium poppy, being key periods for opium gum forming, can be selected as an indicator for estimating opium yield. LAI can quickly be surveyed in situ using special equipment (Jonckheere et al., 2004; Weiss et al., 2004). Using a simple linear model, it efficiently provides opium
yield information. Based on LAI measurements, instead of on traditional harvesting means, it can thus quickly provide accurate opium yield information, without subjective influences e.g. from harvesters.

The opium yield estimation model is typically an empirical model. If the model present in this study is used in other regions, a new regression analysis based on the field survey data should refine the coefficients. Moreover, the current investigation is done in an area where opium poppy is planted as a general crop and by means of an intensive cultivation. In illegal cultivation regions, however, where the opium poppy cultivation is scattered, the applicability of the model needs to be verified.

The LAI can be derived from remote sensing data and is a hot research topic of remote sensing technique (Fang et al., 2003). LAI estimation has two main approaches. One is through the empirical relationship between LAI and vegetation indices (Xavier and Vettorazzi, 2004) or spectral reflectance (Guan and Nutter, 2002), the other one is by means of inversion of physical canopy reflectance models (Darvishzadeh et al., 2008). Thus, LAI estimation during the flowering and harvesting periods of opium poppy provides a bridge between opium yield estimation and remote sensing. It also could provide more precise opium production information than the field survey, because the opium yield of poppy is not symmetrically distributed, and sampling method may provide bias estimation. Furthermore, it is safer to collect opium production information using remote sensing technique, for the regions with opium poppy cultivation are always dangers, both in natural (high mountains) and social (armed criminals) aspects. In addition, there is a considerable saving in collecting costs for opium yield information at large scale.

The opium yield estimation method is promising to be applied in the major opium production regions where opium poppy is cultivated in a concentrated way, such as in Afghanistan and North Myanmar, being also the focuses of UNODC monitoring programs. However, different regions may have various planting characters. Therefore, it is necessary to collect field data for building local opium yield estimation models. Using remote sensing technique instead of sampling and field survey method, an opium yield estimation model will allow a solid spatial coverage to estimate opium production, once it has been built on the basis of growth season specific ground surveys.

6. Conclusions

This study is designed to identify a poppy biophysical variable for opium yield estimation. The results indicate that LAI in flowering and harvesting periods of opium poppy is an effective biophysical indicator. The LAI can be quickly measured using special equipment \textit{in situ}. LAI can also be retrieved from remote sensing data. Therefore, LAI in flowering and harvesting periods of opium poppy provides the bridge joining opium yield estimation and remote sensing technique.

Future work will further concentrate on opium yield estimation using remote sensing. It will be based locally on LAI measurement in opium poppy concentrated regions. Further, the opium yield in this study refers to crude opium gum yield, and the content of morphine in crude opium gum is not considered. Morphine being the main raw material to produce heroin, its potential production is the most relevant information. These and other steps we hope to be able to make in the near future.
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