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The agronomy and economy of illicit indoor cannabis cultivation

by

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Thesis submitted in fulfilment of the requirement for the degree of Doctor (PhD) in Applied Biological Sciences

Cite as: Vanhove, W. (2014). The agronomy and economy of illicit indoor cannabis cultivation. PhD thesis, Ghent University, Belgium.

Dutch translation of the dissertation title: De agronomie en economie van de illegale binnenteelt van cannabis.

ISBN 978-90-5989-681-9

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LIST OF ABBREVIATIONS

AGP	Angiosperm Phylogeny Group
BVOC	Biogenic Volatile Organic Compound
CBD	Cannabidiol
CBN	Cannabinol
DCP	Directorate of Crime against Persons
EC	Electrical Conductivity
EMCDDA	European Monitoring Centre for Drugs and Drug Addiction
EU	European Union
GDD	Growing Degree Days
HPS	High Pressure Sodium
LSD	Least Significant Difference
NFT	Nutrient Film Technique
OCG	Organised Crime Gang
PAR	Photosynthetically Active Radiation
RH	Relative Humidity
RIC	Regulation Intelligent Controller
ROC	Rate of Return on Costs
ScrOG	Screen-of-green
SOG	Sea-of-green
THC	Δ^9-tetrahydrocannabinol
UNODC	United Nations Office on Drugs and Crime

ACKNOWLEDGEMENTS

This PhD manuscript could only be completed with the support of a number of people, to who I would like to express my greatest gratitude. I first of all thank my promoter, Prof. dr. ir. Patrick Van Damme, who has been my mentor for more than 10 years, encouraged me to take on the challenge of this interdisciplinary research, and guided me from alpha to omega in writing the doctoral manuscript.

I would further like to thank Prof. dr. Brice De Ruyver and Tim Surmont of the Institute for International Research on Criminal Policy (IRCP) (Ghent University), for teaming up with us in the multidisciplinary project that eventually led to the present manuscript. Their contributions and comments have significantly increased the quality of the PhD. The field work of Tim Surmont in which he interviewed 27 cannabis chain actors, formed the basis of the financial analysis reported in chapter 5 of the present PhD. It was also Tim Surmont who performed price data analyses from the latter interviews and who revealed farm gate pricing mechanisms in the cannabis value chain. Identifying and interviewing drug respondents can be a hazardous job. We owe Tim a lot for performing this task. Many thanks also to Benny Van Camp, Judicial Commissioner of the Directorate of Crime against Persons (Belgian Federal Police) and his team for their highly valued advice on the setup and improvement of our cannabis plantation and for the regular follow-up of our project.

I am very grateful to the Belgian Science Policy (BELSPO) for funding the project 'Yield of Illicit Indoor Cannabis Plantations' (YILCAN) that formed the basis of the present PhD-manuscript. We would also like to thank the Department of Infrastructure and Facility Management of Ghent University – Dario Giacomucci in particular – for enabling the construction and security of our cannabis growth room. Thanks also to Dr. Natalie Meert of the National Institute of Criminalistics and Criminology (NICC - Brussels) for determining cannabinoid concentrations in our samples.

I would like to thank Prof. dr. ir. Guido Van Huylenbroeck, Prof. dr. Brice De Ruyver Brice (Ghent University), Prof. Ladislav Kokoska (Czech University of Life

Sciences), Prof. dr. ir. Dirk Reheul (Ghent University), Prof. dr. ir. Roeland Samson (University of Antwerp) and Mr. Benny Van Camp (Federal Police) for accepting to be member of the examination committee and for their valuable comments that have raised the present manuscript to a higher level. Special thanks to dr. Jan De Neve and dr. ir. Mathias Cougnon (Ghent University) for statistical counselling.

I would further like to express my special gratitude to a number of people that have played an essential role in the research process that led to the present PhD work. First of all to Johan Geirnaert, my 'partner in crime' in all practical botanical and horticultural work that was required during experiments. Without Johan's lifelong experience and critical insights in plant production, the present work would have simply been impossible. My colleagues at the Laboratory of Tropical and Subtropical Agriculture and Ethnobotany have always been an enjoyable support and distraction in times of data processing and manuscript writing. Thanks a lot Annita, Machteld, Johan, Isabel, Betty, Emmy, Sitske, Aissata, Codou, Suzy, Marème, Sabine, Ina, Evert, Bernard, Patrice, Marleen, Sofie, Riziki, Vahid, Seyni, Mohammad, Ali, Ahmed, Omar, Jila, Lou, Celine, Kaat, Amadou, Daniela, Ann, Arne, Charlie, Hamid-Reza, Achille, Jean, Claire, Hamid Asgari, Hamid Sodaezadeh, Solomo, Charles, Julius, Ebenezar, Xavier, Veerle, Sara, Sidi, Cecilia and many more who have been with us for short or long stays to work on their own PhDs.

To conclude with, a special word of gratitude to my wife Ineke and my children Bonnie and Teo who have made the road to PhD a lot smoother by providing a warm and cheerful home. I thank my mom for her continuous support for, and interest in my work. Last but not least, I would like to dedicate this thesis to my late father, from whom I inherited an inquisitive attitude and profound interest in science and technology. In completing this work, he is missed more than ever.

SUMMARY

The present doctoral research addresses a number of questions that were initially formulated by the Belgian Police and judiciary on yield of illicit indoor cannabis cultivation in Belgium and on the profits gained by illicit cannabis growers. Increased law enforcement since 1995 in the Netherlands to try to tackle criminal aspects of the illicit cannabis sector resulted in a so-called 'waterbed effect' whereby Dutch cannabis growers set up new cannabis plantations in Belgium, often in collaboration with Belgian growers who operate indoor plantations as part of a Dutch-run network. As a consequence, the Belgian police increased investigation efforts on cannabis plantations. The latter approach resulted in increasing numbers of cannabis plantations confiscated by the Belgian Police (979 confiscated plantations in 2010). In court, besides fines and/or incarceration, illicit growers face confiscation of the profits they presumably obtained during the time they operated their plantations. For calculation of the latter profits, the Belgian judiciary currently uses results of a Dutch study from 2006 in which a reliable yield estimate for indoor-grown cannabis was set at 28.1 g per plant. However, observation of numerous indoor cannabis plantation sites by the Belgian Police led to the conclusion that real cannabis yield nowadays exceeds by far 28.1 g per plant. On the other hand and based on internet information and judicial file information, Belgian judiciary currently assumes that cannabis is sold by growers at a price of € 3 per g. However, the Belgian police and judiciary have no reliable information on the price fixing mechanisms in the Belgian cannabis sector and consequently have no scientific ground to define the sales price of € 3 per g currently used in prosecution.

Our research addressed these problems first of all by setting up a cannabis plantation that resembles typical real-case indoor cannabis plantations in terms of size, varieties used and environmental conditions. In the growth room, especially designed for our research, three cannabis growth cycles were performed.

In the first cycle (20 May – 30 July 2010), we investigated the production factors that determine yield (expressed as weight of dry cannabis female flower buds per plant and per cultivation surface unit) and quality (concentrations of the

cannabinoids THC, CBN and CBD) of indoor cannabis. The experiment contained three cultivation factors that were combined in a full factorial design: i) light intensity (400 W per m² and 600 W per m²); ii) plant density (16 and 20 plants per m²); and iii) variety (Super Skunk, Northern Light #5 x Haze, White Widow and Big Bud). Plant density factor was applied to 2 whole plots (each 8 m²) and that were each divided in two split-plots (4 m²) with different light intensities. Each split-plot was further divided in 4 split-split-plots (1 m²), each containing a different cannabis variety. Considering only main treatment effects, it was found that average yield of plants cultivated under 600 W lamps (20.1 g per plant) was significantly ($p < 0.05$) higher than average yield of plants cultivated under 400 W lamps (11.7 g per plant). Average yield per plant of plants cultivated at a density of 16 plants per m² (17.6 g) was significantly ($p < 0.01$) higher than average yield per plant of plants cultivated at a density of 20 plants per m² (14.5 g). However, no significant differences in plant yield could be elucidated between different plant densities when yield is expressed in g per m². Highest yield was found for the Super Skunk and Big Bud varieties (average yield of 19 g per plant 18 g per plant, respectively) which also exhibited the highest THC concentrations. Other growth factors did not have any influence on THC concentrations. Variation in other cannabinoids (between 0.1 % and 0.3 % for CBN and between 0.2 % and 0.4 % for CBD) was very low and was unaffected by the considered factors. Results further show that plant density and light intensity are additive factors whereas the variety factor significantly interacts with both plant density and light intensity factor in their effect on cannabis yield. Because of sub-optimal environmental control and inexperience of researchers, yield figures in the first grow cycle are below the currently used value of 28.1 g per plant. Results of the first cycle only reveal the significance of the effect of, and interaction between different growth factors.

A second cycle (30 September – 30 December 2010) was subsequently performed to test the effect of densities lower than those of the first cycle and to verify whether less intense fertilizer applications significantly affect cannabis yield. The second cycle consisted of two full factorial split-plot experiments that were combined in a single growth cycle. In the first, the influence of, and interaction between i) three plant densities (9, 12 and 16 plants per m²) (in whole plots); and ii) the 4 cannabis varieties (in split-plots) used in the first cycle, on the yield of indoor cannabis, was studied. The second experiment was performed on plots with plant

densities of 16 plants per m² only. The influence of, and interaction between i) two levels of fertilization (i.e. a whole plot with a fertilization schedule equal to that of the first cycle, and another whole plot with a more basic fertilization schedule); and ii) the 4 cannabis varieties (in split-plots) used in the first cycle on the yield of indoor cannabis, was evaluated. Results of the first experiment confirm the finding of the first cycle that yield per plant increases significantly with decreasing plant densities, but that these differences no longer prevail when yield is expressed per m². When fertilizer application was lowered to a basic level, average cannabis yield decreased with 188 g per m² (33 %) in comparison with blocks with full fertilization. However, results of the second growth cycle must be interpreted with some reserves. Temperature in the growth room was suboptimal during the whole second growth cycle, resulting in a high rate of plant withering (43 % of all plants). As a result, also the second growth cycle did not allow making a reliable estimate of the yield of an indoor cannabis plantation.

The third cycle (14 February – 29 April 2011) consisted of a full factorial split-plot design with two replicates of two factor combinations: i) 2 plant densities (in whole plots with 12 and 16 plants per m²); and ii) 4 cannabis varieties (split-plots with varieties Big Bud, Skunk #1, Silver Haze #9 and an unknown variety propagated from a plant confiscated by the Belgian Police and included as a reference). Average yield per plant was found to be significantly ($p < 0.01$) different between plant densities, but just as in the first two growth cycles, statistical differences between plant densities did no longer prevail when yield was expressed as g per m². Results also show there is no interaction between the factors density and variety in their effect on indoor cannabis yield. It was concluded that for practical use in profit confiscation, yield of a Belgian indoor cannabis plantation can be reliably estimated by the lower-bound of the one-sided 95 % confidence interval for the yield of plants produced at densities of 12 and 16 plants per m², which is in both cases set at 575 g per m². The latter imply average per plant yield figures that are considerably higher than the figure currently used by the Belgian police and judiciary (28.1 g per plant). From our experiment, we conclude that per plant yield is at least 48 g for plants grown at a density of 12 plants per m², and 36 g for plants grown at a density of 16 plants per m².

Prices and pricing mechanisms of Belgian indoor cannabis cultivation were investigated by means of interviews with respondents selected through snowball sampling (i.e. one respondent identifies the following). Results reveal that i) the Belgian cannabis market chain is highly complex; ii) unit prices are predominantly determined by transaction sizes; iii) but also that a set of product- and socially-related price-fixing mechanisms have an equally important role. At grower level, respondents reported prices for 1 g of dry cannabis buds to range € 3.00 - € 4.25.

In order to shed light on the profit margins gained by illicit indoor cannabis growers in Belgium, a cost-benefit analysis was performed using real-situation data of four growers, and taking fixed and variable material costs, as well as opportunity costs into account. Benefit per growth cycle was calculated based on the yield estimate (575 g per m²) determined in our cannabis growth cycle experiments and on price information retrieved from interviews with growers whose plantations were used as cases in our analysis. Benefits were adjusted by multiplying gross benefits with (1-π), in which π is the grower's risk of getting caught. Finally, benefits and return on costs (ROC) were calculated over a 1 year period (4 cycles). Results show that in all cases benefits as well as ROCs are considerable, even after one growth cycle. Highest profitability was found for large-scale (600 plants, ROC = 6.8) and mid-scale plantations (150 plants, ROC = 6.0). However, industrial plantations (23,000 plants, ROC = 1.4) and micro-scale plantations (5 plants, ROC = 2.8) are also highly remunerative. A shift of police focus away from micro-scale growers, to large-scale and industrial scale plantations would influence the latter's benefits because it would increase the risks of getting caught. However, sensitivity analysis shows that this does not significantly influence the conclusions on the magnitude of profits or on ROCs obtained by different types of indoor cannabis plantations. Some 20 % of cannabis plantations confiscated by the Belgian police are micro-scale plantations that are most probably operated by hobby-growers that have no link with criminal networks.

In order to make correct estimates of the yield of soil-based cannabis plantations, we recommend confiscating police intervention staff to record at least: i) total number of plants; ii) the surface covered with plants (m²); iii) the number of assimilation lamps per m² (by counting the number of lamps and dividing it with

growth surface); and iv) the power of the lamps (in W per lamp). Yield and profit margins of indoor cannabis plantations are likely to evolve. As a consequence, results of our research might be outdated soon. Further research should consequently evaluate the effect on cannabis plantation's yield and profit margins of other, or newly emerging growth factors not considered in the present study (e.g. hydroponics, newly developed varieties, LED-lights).

SAMENVATTING

Voorliggend doctoraatsonderzoek beantwoordt een aantal vragen van de Belgische federale politie en justitie omtrent de mogelijke opbrengstcijfers en verkoopsprijzen in de illegale Belgische binnenteelt van cannabis. In 1995 werden in Nederland de politionele inspanningen voor de bestrijding van de criminele aspecten van cannabisteelt en –handel gevoelig verhoogd. Dit resulteerde in het zogenaamde 'waterbedeffect' waarbij Nederlandse cannabistelers nieuwe plantages installeren in België, vaak in samenwerking met Belgische telers die de plantages uitbaten als onderdeel van een Nederlands drugsnetwerk. Ook de Belgische politie heeft zich, als gevolg van deze evolutie, meer intensief op de opsporing en ontmanteling van cannabisplantages gericht. Als gevolg daarvan worden in België elk jaar meer en meer ontmantelingen van cannabisplantages gemeld (979 plantages in 2010). De telers riskeren niet enkel boetes of gevangenisstraffen, maar worden meestal ook veroordeeld tot het terugbetalen van de vermogensvoordelen die werden bekomen tijdens het uitbaten van de cannabisplantage. Voor de berekening van deze vermogensvoordelen baseert de Belgische justitie zich momenteel op de resultaten van een Nederlandse studie (2006) waarin op basis van lineaire regressie van de opbrengst van 77 inbeslaggenomen plantages, een oprengst van 28,1 g per plant als betrouwbare maatstaf voor de binnenteelt van cannabis werd naar voren geschoven. De Belgische politie observeert tijdens de talrijke inbeslagnames van cannabisplantages echter frequent planten waarvan de opbrengst duidelijk veel groter is dan 28,1 g per plant. Op basis van internetgegevens en informatie uit gerechtelijke dossiers, veronderstelt de Belgische justitie verder dat cannabis door de telers verkocht wordt aan een prijs van € 3 per g. De Belgische politie en justitie hebben echter geen betrouwbare informatie over de prijszettingsmechanismen in de Belgische cannabissector en beschikken bijgevolg niet over een wetenschappelijk basis voor de momenteel in de verbeurdverklaringen gehanteerde verkoopsprijs van € 3 per g.

In het voorliggende doctoraatsonderzoek werden deze problemen aangepakt door eerst en vooral een cannabisplantage op te zetten die zo goed mogelijk de

teeltomstandigheden (variëteiten en omgevingsvariabelen) in een reële, illegale cannabisplantage nabootst. Als gevolg hiervan werden er in totaal drie experimentele cannabisteeltcycli uitgevoerd in een speciaal hiervoor ingerichte teeltruimte.

Tijdens de eerste cyclus (20 mei – 30 juli 2010) werd de invloed van bepaalde teeltfactoren op de opbrengst (uitgedrukt in het aantal gram gedroogde, vrouwelijke cannabisbloemen) en de kwaliteit (concentraties aan cannabinoïden THC, CBN en CBD) in de binnenteelt van cannabis, nagegaan. Het experiment omvatte 3 teeltfactoren die werden gecombineerd in een factoriële split-plot proefopzet: i) lichtintensiteit (400 W per m² en 600 W per m²); ii) plantdichtheid (16 en 20 planten per m²); en iii) variëteit (Super Skunk, Northern Light #5 x Haze, White Widow en Big Bud). De factor plantdichtheid werd toegepast in twee *whole plots* van 8 m². Daarin werden twee *split-plots* van 4 m² aangebracht met in elk een van de twee lichtintensiteiten. Elke *split-plot* werd bestond uit 4 *split-split-plots* van 1 m² met telkens één van de 4 cannabisvariëteiten. Indien enkel de hoofdeffecten in beschouwing worden genomen, bleek dat de gemiddelde opbrengst van planten in blokken met 600 W lampen (20,1 g per plant) significant ($p < 0,05$) hoger was dan de gemiddelde opbrengst van planten in blokken met 400 W lampen (11,7 g per plant). De gemiddelde opbrengst per plant in blokken met een dichtheid van 16 planten per m² (17,6 g) was significant ($p < 0,01$) hoger dan de gemiddelde opbrengst in blokken met een dichtheid van 20 planten per m² (14,5 g). Er werden echter geen significante opbrengstverschillen gevonden tussen planten met verschillende plantdichtheden wanneer de opbrengst werd uitgedrukt in g per m². De hoogste opbrengst werd behaald met de variëteiten Super Skunk en Big Bud (respectievelijk 19 g en 18 g per plant) die ook de grootste THC-gehaltes bleken te bevatten. Andere teeltfactoren hadden geen invloed op het THC-gehalte. Er werd een heel kleine variatie vastgesteld in de gehaltes aan andere cannabinoïden (tussen 0,1 % en 0,3 % voor CBN en tussen 0,2 % en 0,4 % voor CBD) die verder niet door de beschouwde teeltfactoren werden beïnvloed. De resultaten tonen verder aan dat plantdichtheid en lichtintensiteit additieve factoren zijn, terwijl er een significante interactie optreedt tussen de factor variëteit enerzijds, en de factoren plantdichtheid en lichtintensiteit anderzijds, in hun effect op de cannabisopbrengst. Als gevolg van de sub-optimale teeltomstandigheden en de onervarenheid van de onderzoekers in de eerste teeltcyclus, bevinden de bekomen opbrengstcijfers zich onder de momenteel

gehanteerde waarde van 28,1 g per plant. De resultaten van de eerste teeltcyclus onthullen dan ook enkel de significante van, en de interactie tussen verschillende teeltfactoren in de binnenteelt van cannabis.

Na deze eerste testronde werd een tweede cyclus (30 september – 30 december 2010) opgezet waarin het effect van plantdichtheden lager dan deze uit de eerste cyclus werd getest, en waarin werd nagegaan of een minder intensieve bemesting een significant effect heeft op de opbrengst. De teeltcyclus bestond uit twee volledige, factoriële *split-plot* proefopzetten die werden gecombineerd in één enkele teeltcyclus. In de eerste proefopzet werd de invloed van, en interactie tussen i) drie plantdichtheden (*whole plots* met 9, 12 en 16 planten per m²); en ii) de 4 variëteiten (*split-plots* uit de eerste cyclus op de opbrengst van de binnenteelt van cannabis nagegaan. De tweede proefopzet bestond enkel uit plots met een plantdichtheid van 16 planten per m². Hierin werd de invloed van, en interactie tussen i) twee bemestingsniveaus (één *whole plot* zoals toegepast in de eerste cyclus, en een andere *whole plot* met een minder intensief basisniveau); en ii) de 4 variëteiten (in *split-plots*) uit de eerste cyclus op de opbrengst van de binnenteelt van cannabis nagegaan. De resultaten van de eerste proef bevestigen de bevindingen uit de eerste cyclus, met name dat de opbrengst per plant significant toeneemt bij afnemende plantdichtheden, maar dat deze verschillen zich niet langer voordoen wanneer de opbrengst wordt uitgedrukt in g per m². Wanneer het bemestingsniveau wordt verlaagd tot een basisniveau, verlaagt de gemiddelde cannabisopbrengst met 188 g per m² (33 %) in vergelijking met de opbrengst in blokken met een intensieve bemesting. De resultaten van de tweede groeicyclus moeten echter omzichtig worden benaderd. De temperatuur in de teeltruimte was gedurende de hele cyclus suboptimaal, wat resulteerde in een hoog aantal (43 %) verwelkte planten aan het einde van de teeltcyclus. Bijgevolg kon ook de tweede teeltcyclus geen betrouwbaar opbrengstcijfer voor de binnenteelt van cannabis worden bekomen.

De derde cyclus (14 februari – 29 april 2011) bestond uit een volledige, factoriële *split-plot* proefopzet met twee herhalingen, waarin 2 factoren werden gecombineerd: i) 2 plantdichtheden (in *whole plots* met 12 en 16 planten per m²); en ii) 4 cannabisvariëteiten (*split plots* met de variëteiten Big Bud, Skunk #1, Silver Haze #9, en een onbekende variëteit die werd vermeerderd op basis van stekken van een

door de federale politie geconfisceerde plant en die in de proef als praktijkreferentie werd opgenomen). De resultaten tonen aan dat de gemiddelde opbrengst per plant significant ($p < 0,01$) verschilt tussen blokken met verschillende plantdichtheden, maar dat er - net als bij de eerdere cycli - als de opbrengst wordt uitgedrukt in g per m², zich geen statistische verschillen tussen de hier geteste plantdichtheden voordoen. De resultaten tonen verder aan dat er geen interactie is tussen de factoren dichtheid en variëteit in hun effect op de opbrengst bij de binnenteelt van cannabis. Er wordt besloten dat voor praktisch gebruik in de verbeurdverklaring van vermogenswinsten, de opbrengst bij de binnenteelt van cannabis betrouwbaar kan worden geschat via de ondergrens van het 95 % eenzijdig betrouwbaarheidsinterval (575 g per m²), dat werd berekend voor blokken met 12 en 16 planten per m². Dit betekent dat de gemiddelde opbrengstcijfers per plant aanzienlijk hoger zijn dan het cijfer dat momenteel door de Belgische politie en justitie wordt gehanteerd (28.1 g per plant). We concludere uit ons experiment dat de opbrengst per plant ten minste 48 g bedraagt voor planten geteeld aan een dichtheid van 12 planten per m² en ten minste 36 g bedraagt voor planten geteeld aan een dichtheid van 16 planten per m².

Prijzen en prijszettingsmechanismen in de binnenteelt van cannabis in België werden bestudeerd door middel van interviews met respondenten die middels een sneeuwbalsteekproef, waarin een respondent een volgende identificeert, werden geselecteerd. De resultaten tonen aan dat i) de Belgische cannabissector heel complex is; ii) eenheidsprijzen voornamelijk worden bepaald door transactievolumes; maar ook dat iii) een aantal aan het product en sociale factoren verbonden prijszettingsmechanismen een belangrijke rol spelen. Op het niveau van de teler werden verkoopprijzen tussen € 3,00 en € 4,25 per g gerapporteerd.

Om een beter zicht te krijgen op de winsten die illegale cannabistelers in België opstrijken, werd een financiële analyse verricht op basis van gegevens van reële gevalstudies waarbij vaste, variabele en alternatieve kosten in rekening werden gebracht. De omzet per teeltcyclus werd berekend op basis van het opbrengstcijfer (575 g per m²) dat werd bepaald in de teeltexperimenten (cfr. *supra*) en aan de hand van prijsinformatie die werd bekomen uit interviews met telers die als gevalstudies in de analyse werden opgenomen. De omzet werd vervolgens aangepast voor het risico dat de teler loopt om gevat te worden. Tenslotte werden de omzet en de *return on*

costs (ROC) berekend voor een cannabisteelt van 1 jaar (4 cycli). De resultaten tonen aan dat in alle gevallen zowel de omzet als de ROC, zelfs reeds na 1 teeltcyclus, aanzienlijk zijn. De hoogste winsten werden bekomen voor een grootschalige plantage (600 planten, ROC = 6,8) en een plantage van gemiddelde omvang (150 planten, ROC = 6,0). Niettemin bleken een industriële plantage (23.000 planten, ROC = 1,4) en een plantage op microschaal (5 planten, ROC = 2,8) eveneens bijzonder winstgevend. Indien de politie haar focus nog meer zou richten op de aanpak van grootschalige en industriële plantages, zouden de omzetcijfers worden beïnvloed als gevolg van een grotere kans om gevat te worden. Een sensitiviteitsanalyse toont echter aan dat dit geen impact zou hebben op de conclusies met betrekking tot de winstgevendheid van de onderscheiden telerstypes. Ongeveer een vijfde van de door de Belgische politie inbeslaggenomen cannabisplantages bevatten minder dan 5 planten. Die worden bijgevolg heel waarschijnlijk uitgebaat door hobbytelers die geen deel uitmaken van criminele netwerken.

Om correcte opbrengstschattingen in de binnenteelt van cannabis in potgrond te verzekeren, raden we het politiepersoneel bij inbeslagname aan om op zijn minst de volgende parameters te bepalen: i) het totaal aantal planten in de plantage; ii) de grondoppervlakte (m²) die met planten is bedekt; iii) het aantal assimilatielampen per m² (bekomen door het totaal aantal lampen te delen door de totale teeltoppervlakte); en iv) het lampvermogen (in W per per lamp). De opbrengst en de winstmarges die in de binnenteelt van cannabis worden bekomen, zullen vermoedelijk in de toekomst verder evolueren. De resultaten van ons onderzoek kunnen bijgevolg snel achterhaald zijn. Toekomstig onderzoek zou om die redenen het effect op de opbrengst en winstmarges moeten evalueren van andere of nieuwe teeltfactoren die in het huidige onderzoek niet werden beschouwd (bv. hydroteelt, nieuwe variëteiten, LED-verlichting).

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CHAPTER 1 Introduction

1.1. Problem statement

Cannabis (*Cannabis* spp.) has been used for fibre, food, medicine, ceremonies and as a recreational drug for at least 10,000 years (Merlin, 2003). Today, cannabis (frequently also called marijuana) is predominantly renowned for its psychoactive drug properties. Since the 1960s, the popularity of cannabis as a recreational drug steadily and globally increased. Today, cannabis is the most widely and universally used illegal drug in the world (Potter *et al*., 2011). The United Nations Office on Drugs and Crime (UNODC) estimated the number of regular cannabis users around the world in 2010 to be between 119 and 225 million (UNODC, 2012). Police data on number and quantities of cannabis seizures, and surveys with European citizens performed by The European Monitoring Centre for Drugs and Drug Addiction (EMCDDA) reveal that in Europe, cannabis demand and supply has continuously risen since 1990 (EMCDDA, 2013). It has furthermore been observed that the cannabis supply chain is increasingly overtaken by organized crime (Bovenkerk & Hogewind, 2002; EMCDDA, 2013a; Plecas *et al*., 2002; Spapens *et al*., 2007), with a concomitant rise in violence (Walker *et al*., 1998). Decorte (2010a), however, states it is extremely difficult to empirically verify the exact nature and intensity of criminal group involvement in the cannabis market.

Belgium also follows this global trend. However, the recent increase in the number of cannabis plantations in Belgium is also explained by the so-called 'waterbed' effect; i.e. a shift of indoor cannabis growing from the Netherlands to Belgium as a result of a shift in drug policies in the former country. Due to increased involvement of criminal organisations in the cannabis market chain, the Dutch police and judiciary since 1995 increased pressure on coffeeshops (i.e. establishments where sales of small quantities (< 5 g) of cannabis are tolerated (Maris, 1999) under the Dutch Opium Law (continuously adapted since 1919)), and stepped up criminal investigation and subsequent legal proceedings (van Ooyen-Houben, 2006). One of the main drivers was increasing international pressure on the Netherlands to contain cannabis production within its own borders. According to neighbouring countries, the Dutch cannabis tolerance policy attracts their youth to buy illicit drugs in the Netherlands. Moreover, the increasing stream of international drug tourists towards

coffeeshops and other dealing premises causes potential public nuisance to local citizens (Boekhout van Solinge, 1996; De Ruyver *et al.*, 2007; Surmont, 2007). Coffeeshops are often supplied by cannabis-producing networks (Spapens *et al*., 2007). As a result, by the end of the 1990s, cannabis-related problems in the Netherlands were mainly tackled by focusing on the latter networks (Boekhout van Solinge, 2004; Korf *et al*., 2001; van de Bunt, 2006; van Ooyen-Houben, 2006).

As a result of their highly dynamic and adaptive character, Dutch drug networks subsequently found a new operation base in Belgium. This so-called displacement was also opportunity-driven: initially, plantations were not easily detected by the Belgian police, because, contrary to their Dutch colleagues, they did not have a long tradition in tracing cannabis plantations and the networks they operate in (Spapens *et al*., 2007; Van Camp, 2008). Displacement of cannabis growing and improved criminal investigation consequently explain the rise in number of seizures in Belgium. In 2003, only 35 cannabis plantations were seized by the police. By 2007, this number had risen to 466 and by 2012 to 1,111. Half of these were large plantations with more than 50 plants, even though an increase in seizure is reported for all plantation sizes (Fig. 1.1). Although these figures are partly explained by increased interest in and investigation of illicit cannabis growing by the Belgian police, indoor cannabis growing in Belgium is undeniably on the rise. Many of the discovered plantations are set up, or managed, by Dutch criminal entrepreneurs or persons having at least a certain connection with the Netherlands, whereas most of the growth materials used are sourced from Dutch growshops (i.e. specialized shops selling seemingly normal horticultural material, which combined in the proper setting nevertheless clearly yield a cannabis cultivation environment) (Fijnaut & De Ruyver, 2008; Spapens & Fijnaut, 2005; Van Camp, 2008).

Judicial response to these activities consists of seizure (and subsequent confiscation) of the profits gained by the perpetrators. Due to the current lack of scientific data, Belgian judiciary is forced to use rough estimates of the profits gained, based on data on crop yield obtained from seized cannabis plantations and on wholesaler prices used in - amongst others - Dutch coffeeshops. Today, the Belgian judiciary uses a crop yield estimate made by the University of Wageningen, The Netherlands (Toonen *et al*., 2006) and set at 28.1 g of dry female flower buds per

plant (lower bound of the one-sided 95 % confidence interval for predicted yield of the median cannabis plantation in their study). For a subsequent calculation of financial profits, the Belgian police currently relies on price data obtained from internet sites, the Dutch police and Belgian judicial files. On the latter basis, the selling price used by commercial cannabis growers is arbitrarily set at € 3 per g cleaned and dried cannabis buds. The Belgian police further assumes that one growth cycle of indoor cannabis can be completed in 11 weeks (Van Camp, 2009). Observations made by Belgian police during confiscation of indoor cannabis plantations during the past few years nevertheless suggest that illicit growers nowadays achieve plant yields that are much higher than 28.1 g per plant. Based on grey literature resources, internet blogs and judicial files, police furthermore assumes that the currently used price criterion of € 3 per g at growers' level needs to be raised.

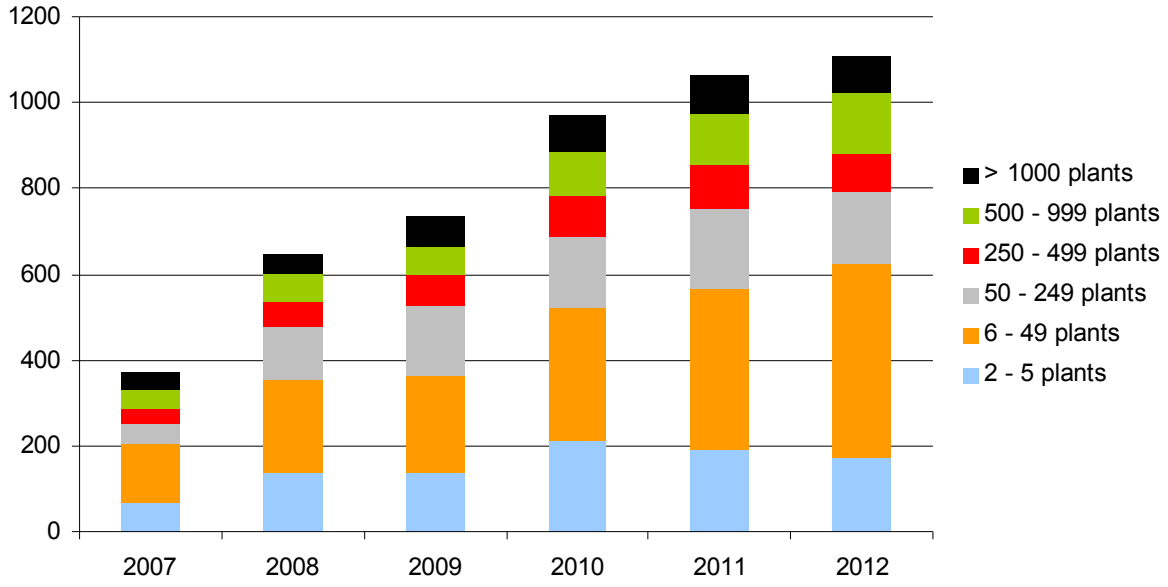

Fig. 1.1. *Number of illicit indoor cannabis plantations in 6 different size categories confiscated between 2007 and 2012 by the Belgian police (unpublished data from the Belgian Federal Police).*

In 2011, the mean retail price of herbal (i.e. flower buds, as opposed to hashish, which is the resin, see § 2.1.3.) ranged from € 5 (Spain) to € 24 (Bulgaria) per gram. The mean retail prices of herbal cannabis rose slightly over the 2006–11 period (9 % and 12 %, respectively) in those EU countries reporting sufficient data for trend analysis (EMCDDA, 2013). Although much data is available on wholesale and retail prices, and on profits in drug markets (EMCDDA, 2013), little is known about the

precise monetized profit rates of indoor cannabis plantations. Police and judiciary assume the latter gains are considerably higher than those of legal economic activities, but formal estimates have never been provided. Due to the economies of scale, large-scale cannabis growing will generate higher volumes of illicit profit which increases the likelihood of criminal gang involvement. However, nowadays, Belgian judiciary makes no distinction in prosecution of cannabis plantations of different scales. According to Decorte (2010a), most small-scale growers constitute a significant segment of the cannabis grower population that has no connection whatsoever with aforementioned criminal gangs. These small-scale growers are usually mere hobbyists who grow cannabis only for themselves and/or to supply a number of close friends, usually without any profit seeking interest. Scientifically underpinned data on profits for different plantation sizes would thus allow the development of a more fine-tuned and differentiated policy towards containing illicit marijuana growing in Belgium. Tolerating small-scale cannabis growing might increase efforts and financial means of police and judiciary to tackle more severe crime and criminal networks behind larger-scale cannabis growing.

Doubts on the accuracy of the yield figure proposed by Toonen *et al*. (2006) are supported by important shortcomings of the latter study. These findings are indeed based on discovery and confiscation of 77 indoor plantations of which yield was estimated by drying and weighing flower buds of 12 plants per confiscated plantation, irrespective of flower development stage. The study correctly accounts for plant density and light intensity as important yield determining factors, but does not take into account variation in crop yield that undoubtedly occurs between different cannabis varieties. Furthermore, the authors merely recorded the presence/absence of fertilizers, without reporting details on the exact nature or doses of fertilizers used.

Recent seizures of Belgian indoor plantations revealed that cannabis cultivation has become increasingly sophisticated, using automated lighting, ventilation and irrigation systems, and fertilization packages that follow technical growth schedules developed by Dutch growth shops (Van Camp, 2009). State-of-the-art knowledge on indoor cannabis production is mainly obtained from so-called 'grey' resources such as the cultivation manuals from Adams (2007), Cervantes (2007) and Green (2001). Peer-reviewed research on *Cannabis* ssp. focuses on medicinal and/or

pharmacological properties (Borrelli *et al.*, 2013; Deiana, 2013; Esposito *et al*., 2013; Pacher, 2013) (only the most recent publications cited) or on issues relating to cannabis use policy and/or criminology (Barratt *et al*., 2012; Bouchard, 2007, 2008; Bouchard *et al*., 2009; Decorte, 2010a, 2010b; Hakkarainen *et al*., 2011; Malm & Tita, 2007; Maris, 1999; Mills, 2012; Potter *et al*., 2011). Agronomic cannabis research has mainly focused on field production and yield of fibre hemp (Amaducci *et al*., 2008; Cosentino *et al*., 2012; Faux *et al*., 2013; Sera *et al*., 2012; Sikora *et al*., 2011; Struik *et al*., 2000; Van Der Werf, 1997; Van Der Werf *et al*., 1995). So far, Toonen *et al*. (2006), Knight *et al*. (2010) and Potter & Duncombe (2011) are the only research teams that reported on agronomic features of indoor cannabis production in The Netherlands, New Zealand and the United Kingdom, respectively.

1.2. Objectives

Based on the problem statement, the present doctoral study has the following objectives:

i) agronomic assessment of the influence of different indoor cultivation factors on cannabis yield and quality;
ii) estimation of a realistic and scientifically sound yield figure of present-day indoor cannabis cultivation that can be used by Belgian police and judiciary in calculating the magnitude of the profits gained in operating indoor cannabis plantations; and
iii) analysis of pricing mechanisms and of the profits gained by growers of different illicit cannabis plantation sizes in Belgium.

The doctoral thesis starts with a literature review on botany, taxonomy and use of *Cannabis* spp., the agronomic aspects of cannabis growing with focus on specific characteristics of indoor cannabis growing, and on the criminal economy of cannabis cultivation (chapter 2). Next, the aforementioned three research objectives will be addressed in chapters 3, 4 and 5 respectively, followed by a general conclusion and recommendations for further research (chapter 6).

CHAPTER 2 Literature review

2.1. Cannabis spp.

2.1.1. Botany

Cannabis spp. is an aromatic, resinous, annual, dioecious, flowering herb (Rana & Choudhary, 2010; Ranalli, 2004), attaining a height of 0.3 – 1.8 m (male plants) and 0.3 – 1.5 m (female plants) (Rana & Choudhary, 2010). Leaves are palmately compound or digitate with serrate leaflets (ElSohly, 2007). Flowers are imperfect, with staminate male and pistillate female flowers. Although *Cannabis* spp. are generally dioecious, many populations have been found to be sexually labile (Hirata, 1924; Mandolino & Ranalli, 2002; Schaffner, 1931), resulting in monoecy with varying ratios of female to male flowers (Truta *et al*., 2002). Male flowers are normally borne on loose panicles and are yellowish green in colour, whereas female flowers are greenish-white and arranged in axillary, crowded spikes (Moliterni *et al*., 2005; Rana & Choudhary, 2010). Male flowers are fig-shaped, incomplete and actinomorphic. Perianth consists of five yellowish tepals. There are 5 stamens, opposite to tepals. Female inflorescences contain 5 to 7 flowers. The ovary is globose, superior and unicarpellary with one ovule. A single leaf bract appeases to the ovary. The dorsal and ventral surface of tepals of the female flower and the ovarian surface are covered with trichomes whose head cells secrete a resin (Rana & Choudhary, 2010) (Fig. 2.2). *Cannabis* spp. are wind-pollinated. The fruit is an achene, oval in shape. Unripe fruits are green, but turn brown on maturity. There is only one seed per fruit. Seeds are small (Ø 3.7 – 4.0 mm), smooth endospermic and brownish in colour (Rana & Choudhary, 2010; Small, 1975) (Fig. 2.1). The chromosome complement of *Cannabis* spp. is 2n = 20 (Small, 1972).

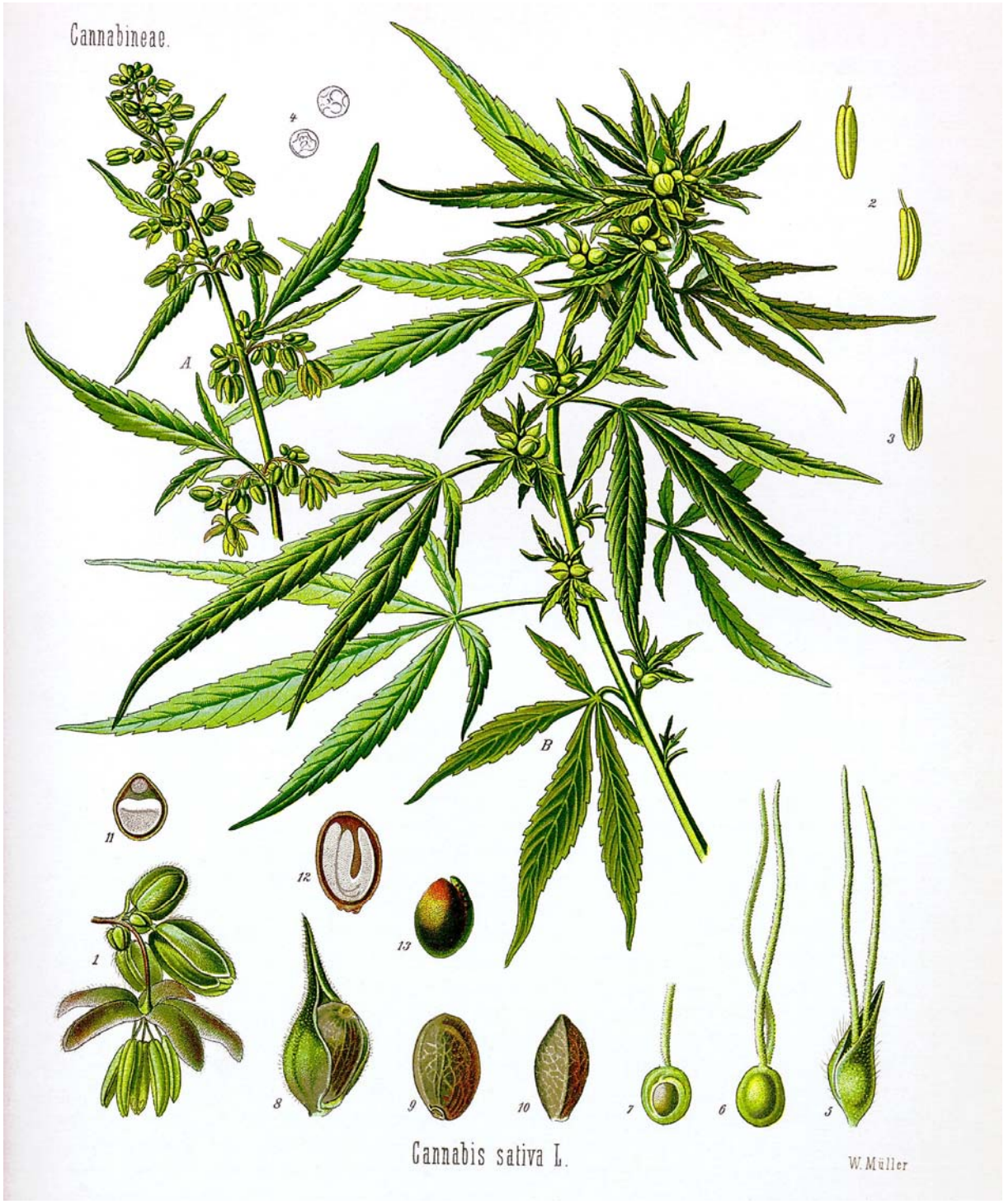

Fig. 2.1. Cannabis sativa *L. A. flowering male; and B. seed-bearing female plant; 1. male flower, enlarged detail; 2. and 3. pollen sac of same from various angles; 4. pollen grain of same; 5. female flower with cover petal; 6. female flower, cover petal removed; 7. female fruit cluster, longitudinal section; 8. fruit with cover petal; 9. same without cover petal; 10. same; 11. same in cross section; 12. same in longitudinal section; 13. seed without hull (Köhler, 1887).*

2.1.2. Taxonomy and classification

Cannabis spp. are believed to have originated in the mountainous regions northwest of the Himalayas. This area coincides with the Central Asiatic centre of crop origin as defined by Vavilov (1951). Genus *Cannabis* is classified in the Cannabaceae family that, according to the third edition of the Angiospem Phylogeny Group (AGP), contains 9 genera: *Aphananthe*, *Cannabis*, *Celtis*, *Gironniera*, *Humulus* (hop)*, Lozanella*, *Parasponia*, *Pteroceltis* and *Trema* (AGP, 2009).

Classification of genus *Cannabis* in species is troublesome (Small, 1979). Since Linnaeus in the 18th century first described *Cannabis* as a monotypic genus, it has been reported to contain between 1 and 13 species, or was divided up in various subspecies and/or varieties. Based on interfertility, chromosome uniformity, chemotypic and phenotypic features, Small and Cronquist (1976) and Small *et al*. (1976) recognized a single *Cannabis* species with two subspecies: *C. sativa* L. subsp. *sativa*, and *C. sativa* L. subsp. *indica*. Other taxonomists of the 1970s, however, distinguished at least three species: *C. sativa*, *C. indica* and *C. ruderalis* (Schultes *et al*., 1974; Anderson, 1974, 1980; Emboden, 1974). *C. sativa* is tall and laxly branched with relatively narrow leaflets, whereas *C. indica* is shorter, conical in shape, and has a thinner cortex and relatively wide leaflets (Hillig, 2005). *C. ruderalis* is short and branchless, grows wild in central Asia and is the only *Cannabis* species that is not used for drug purposes. Recent chemotaxonomic (Hillig & Mahlberg, 2004) and genetic analysis, investigating allozyme variation at 17 gene loci (Hillig, 2005) continues to support the distinction between *C. sativa* and *C. indica*, whereas it is unclear whether *C. ruderalis* is a separate species or rather a variety of *C. sativa*.

Today, breeders of cannabis as a drug plant distinguish 'sativa'- and 'indica'-like cannabis varieties, based on aforementioned morphological differences between *C. sativa* and *C. indica.* Most currently used varieties are hybrids of *C. sativa* and *C. indica*, with varying levels of 'sativa' and 'indica' genes. Renowned examples include Purple Haze and Skunk #1 that predominantly exhibit sativa traits, and Northern Lights and White Widow that mostly express indica features (ElSohly, 2007).

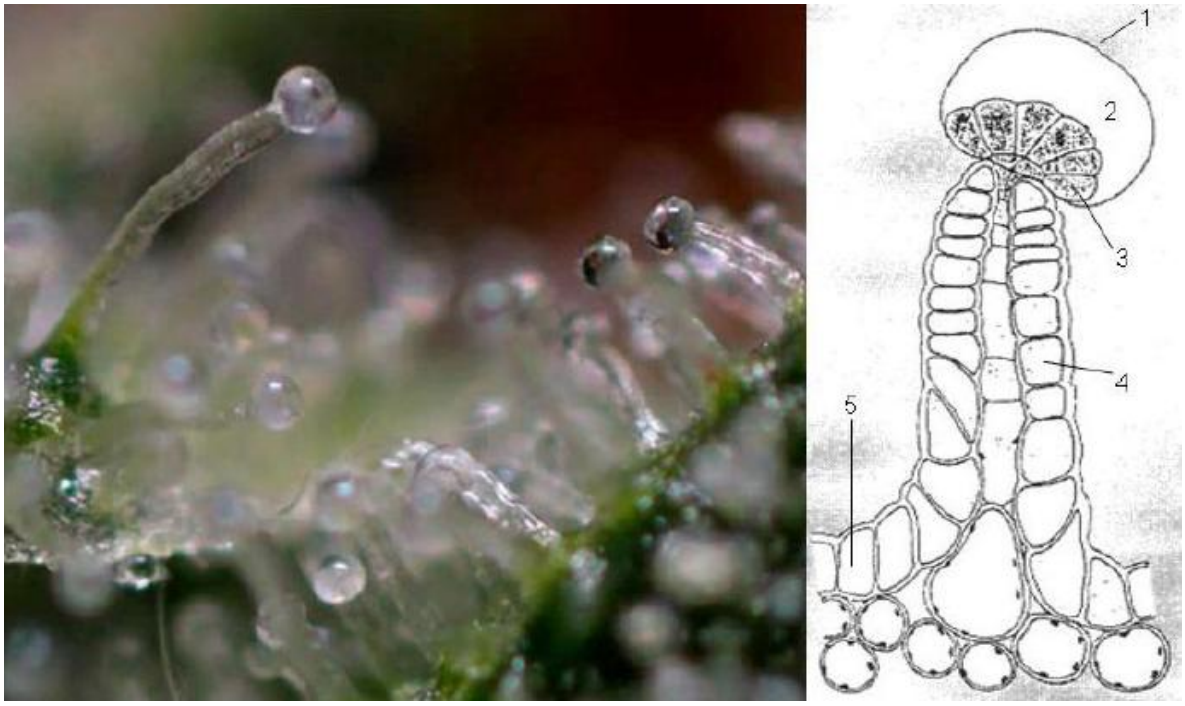

Fig. 2.2. *Microscopic photograph of trichomes on female cannabis flowers (left) and drawing of a cannabis trichome (right). 1. waxy layer; 2. secretory cavity; 3. gland cells; 4. stalk cells; 5. tepal epidermis cell (Source: ElSohly, 2007).*

2.1.3. Psychoactive components

Cannabis spp. produces 85 different cannabinoids - a unique family of terpeno-phenolic compounds that produce the psychoactive effect linked with cannabis consumption (El-Alfy *et al*., 2010). The most abundantly produced cannabinoids in cannabis plants are cannabidiol (CBD), Δ^9-tetrahydrocannabinol (THC) and cannabinol (CBN) (Fig. 2.3). CBN is the primary product of THC degradation. Psychoactive effects of cannabis are predominantly caused by THC, whereas CBN is only mildly psychoactive. Cannabidiol (CBD) is not psychoactive but attenuates the psychoactive effect of THC (Freeman *et al*., 2010; Henquet & Kuepper, 2010).

Since the 1970s, *Cannabis* plants are categorized by their so-called chemotype, more precisely on the basis of overall amounts of THC and of their THC to CBD ratio (de Meijer *et al*., 2003).

Drug plants produce relatively high levels of THC and low levels of CBD, whereas the opposite is the case for non-drug plants (Hillig & Mahlberg, 2004). It is also claimed that 'indica' type cannabis plants have lower THC and higher CBD levels in comparison with 'sativa' type cannabis (ElSohly, 2007). Cannabinoids are secreted by the head cells (resin glands) of glandular trichomes that are densely distributed across the tepals and ovaria of the female flowers (Fig. 2.2). Male plants develop few glandular trichomes and consequently produce few cannabinoids. As a result, male plants are not used for drug purposes. Hashish is nothing more than millions of resin glands that have been rubbed, shaken, or washed from fresh or dry plants and compressed into a dense mass (Carrera, 2006).

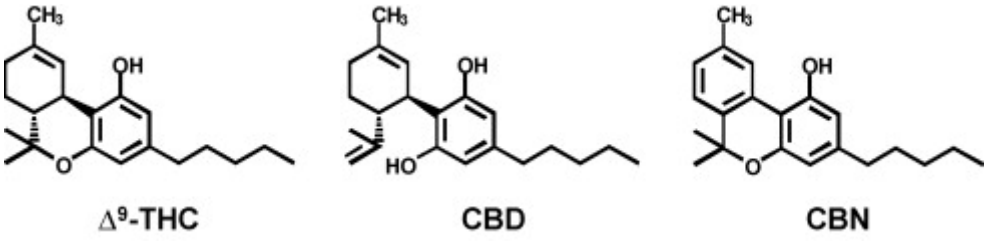

Fig. 2.3. *Chemical structure of the main cannabinoids Δ^9-tetrahydrocannabinol (THC), cannabidiol (CBD) and cannabinol (CBN) (Source: Yamaori* et al*., 2010).*

Once female flowers are pollinated, seed development occurs at the expense of resin production by trichomes. As a result, growers who produce cannabis for drug purposes will avoid pollination by removing male plants from the plantation as soon as sex of flowers can be detected, or by exclusively using female plants by cloning of female parent plants or through feminized seeds. The latter are seeds of dioecious plants that will always result in a female plant. In the case of cannabis, seed feminization is obtained by inducing the formation of male flowers on female plants through application of the plant hormone gibberellic acid (GA_3) or through imposing stress conditions such as an irregular light regime (Adams, 2007; Cervantes, 2006; Freeman *et al*., 1980). Through the above-mentioned treatments, these male flowers contain exclusively X-chromosomes so that the seed resulting from their pollination of female flowers will always be female. A similar technique was used by Eppley and Pannell (2009) in a study of inbreeding of the dioecious species *Mercurialis annua* (Euphorbiaceae). The latter authors applied 0.2 g of the plant hormone 6-benzyl

aminopurine in 19 L of water twice a day to male *M. annua* plants so that the plant produced both female and male flowers. Self-fertilization subsequently resulted in seed from which exclusively (inbred) male plants were produced.

Female flower buds that have developed in the absence of pollination are referred to as 'sinsemilla' cannabis, a noun derived from the Spanish *sin semilla* (without seed) (Green, 2001). Currently, 'sinsemilla' is a general noun for high-potent cannabis varieties, used in indoor cannabis cultivation (McLaren *et al*., 2008; Potter *et al*., 2008).

In so-called *nederwiet* cannabis varieties (i.e. the umbrella term for 'sinsemilla' cannabis strains that are mainly used in Belgium and the Netherlands), THC concentrations rose considerably until 2004. Ever since, THC concentrations in *nederwiet* have stabilized between 15 % and 20 % of dried female flower buds (Rigter & Niesinck, 2010). Also in the United States, the United Kingdom and Italy, it was shown that THC levels of cannabis have increased between the end of the '90s and 2006 (McLaren *et al*., 2008). Although cannabis is not addictive, cannabis use (particularly at adolescent age) increases risk of developing schizophrenia, especially for those who are prone to psychosis (Arseneault *et al*., 2002; Stefanis *et al*., 2013).

2.2. History and criminal aspects of cannabis cultivation and use

Although cannabis was probably already used for fibre or drug properties in its centre of origin during prehistoric times (Lu and Clarke, 1995; Fleming and Clarke, 1998), the first historical records and archaeological data on cannabis cultivation and use date back to 3,000 – 4,000 BC, and are from China. There is evidence of hemp fibre use as a horse rein by the Sredni Stog culture in Ukraine around 4,000 BC (Merlin, 2003). Whether or not cannabis was first used as a fibre, food (seeds), as a psychoactive resin for medicine, ritual or spiritual purposes, or a combination of these applications is uncertain, but the archaeological record provides evidence that it was extensively used in antiquity (Merlin, 2003). Examples include hemp fabric recovered from a Phrygian Kingdom grave mound site at Gordion in Turkey (Godwin, 1967) and hashish found in an Israeli tomb dating back to AD 315 – 392 (Zias *et al*., 1993). The first ethnographic evidence of smoking cannabis comes from Herodotos (446 BC) who, in the fourth book of his *Histories*, describes burning of cannabis seeds by the Scythians in a post-funeral purification ritual (Sherratt, 1995). The first evidence of hemp use in Europe was recovered near Stuttgart in Germany and dates back to the Hallstatt period (500 BC). Cannabis was brought to Africa by sea traders from the Indian subcontinent, possibly as early as the 1st century AD (du Toit, 1980).

By the first half of the 20th century, cannabis was produced and used for both fibre and drug purposes in the Middle East, Central and South Asia, Africa and the Caribbean (Potter *et al*., 2011). Global demand for drug cannabis increased sharply in the 1960s and 1970s as a result of the 'counter-culture'. The latter was a subculture that originated in the USA and the UK and was mainly anti-violent, feminist and raised environmental consciousness. The counter culture extolled the mystical symbolism engendered by the psychoactive effect of cannabis use. As a result of rising demand, formerly traditional cannabis-producing countries such as Morocco and Mexico became major suppliers to respectively European and American consumers. At the same time, international drug control actions were harmonized by the 1961 United Nations Single Convention on Narcotic Drugs that set a clear framework for global anti-drug efforts (UNODC, 2012). Drug trafficking consequently became more risky. As a result, in the 1980s, cannabis was

increasingly produced domestically (i.e. in developed (consuming) countries). After a slight decline in global cannabis use in the 1980s, the drug gained popularity in the 1990s, particularly among teenagers. In order to keep pace with the rising demand for cannabis, both the number and scale of domestic cannabis plantations increased from the same period (Potter *et al*, 2011). Large-scale cannabis plantations (i.e. exceeding a size of just a few plants for personal use), consist of both outdoor as well as indoor (using artificial lighting and climate control) settings (Bouchard & Dion, 2009). It is estimated that as a result of increased domestic production, today most cannabis-consuming countries are self-sufficient for 75 % of their cannabis demand (Potter, 2010). However, the latter estimation is predominantly confined to herbal cannabis. Although in West and Central Europe cannabis resin (hashish) constitutes 84 % of total cannabis seizures by weight, it is assumed that herbal cannabis consumption dominates cannabis product consumption in all European countries. The latter apparent contradiction is explained by the growing domestic production and availability of herbal cannabis as opposed to hashish which is imported from producing countries in North Africa, the Middle East and South-West Asia (EMCDDA, 2013a; 2013b). On a global scale, in recent years a shift of supply of hashish has been observed from Morocco to Afghanistan (UNODC, 2012).

Today, cannabis is cultivated as a drug crop in at least 172 countries. Current worldwide number of regular cannabis users is estimated to be between 119 and 225 million (UNODC, 2012). Since the 1980s, the Netherlands have been an important herbal cannabis supplier within Europe. In the past five years, increases in domestic cannabis cultivation have been reported from Austria, Belgium, Czech Republic, Denmark, Finland, Germany, Hungary, Sweden and the United Kingdom (UNODC, 2012; Potter, 2008). Operators of indoor cannabis cultivation sites increasingly tend to break their initial plantation up into multiple, small-scale plantations rather than operating a single large site. The latter allows them to better avoid detection (smaller sites are easier to hide) and to minimize penalties in case they are caught (Decorte, 2008). Total number of plantation seizures in Europe has increased in the last 10 years, peaking at an estimated 39,000 (3.1 million plants) in 2010, followed by a slight decline (to 36,000 plantations with a total of 4.6 million plants) in 2011. Moreover, Belgium and the Netherlands are trafficking hubs for both hashish and herbal cannabis (EMCDDA, 2013a; EMCDDA, 2013b).

Scientific information on the level of involvement of organised crime in cannabis production in Europe and/or Belgium is scarce. EMCDDA (2013a) reports that Dutch organised crime gangs (OCG), owing to their high levels of expertise, are important facilitators and/or organisers of cannabis production in the EU. As a result of increased pressure from Dutch law enforcement (see also § 1.1. Problem Statement), the latter have extended their activities to neighbouring countries such as Belgium and Germany. In most cases, Dutch OCGs provide Belgium growers with equipment and know-how on cannabis cultivation (Fijnaut & De Ruyver, 2008; Spapens & Fijnaut, 2005; Van Camp, 2008). In recent years, Vietnamese OCGs have emerged as important actors in indoor cannabis cultivation in the EU, particularly in Belgium, Czech Republic, Germany, Ireland, France, Hungary, the Netherlands, Poland, Slovakia and the United Kingdom. Vietnamese-led cannabis plantations are often operated by illegal immigrants working to pay off their passage into Europe (EMCDDA, 2013a). The major factor driving cannabis cultivation by OCGs is financial since a large profit can be gained in a short period (Nguyen & Bouchard, 2010; Potter *et al*., 2011). However, a significant number of - mostly small-scale - cannabis growers in developed countries are motivated by non-financial, ideological reasons (i.e. cannabis growing and use as part of a 'hippie' culture, as was the case with the users of the 1960s counter-culture) (Potter *et al*., 2011).

2.3. Agronomy of indoor cannabis cultivation

Very little reliable information is available on the specific agronomic aspects of indoor cannabis systems. In this section, we will discuss some typically used indoor cannabis cultivation systems, environmental factors affecting cannabis yield and quality (temperature, ventilation, light, relative humidity, etc.) and specific aspects of indoor cannabis growth cycles. Information is derived from grey literature resources (indoor cannabis cultivation manuals) such as those by Adams (2007), Cervantes (2006) and Green (2001). Where the latter authors disagree, or where additional information was available, we have added specific references.

2.3.1. Indoor cannabis cultivation systems

There are many advantages of growing cannabis indoors as opposed to outdoor cultivation. The biggest agronomic advantage is that environmental factors such as temperature, relative humidity, soil conditions and light regime, that are critical for obtaining an adequate yield and the ultimate quality of the harvested product, can be completely controlled by the grower. As a result, environment-independent cannabis cultivation is enabled year-round. In temperate areas, outdoor cannabis cultivation is only possible in the summer period, with only one harvest per year. Apart from these agronomic advantages, indoor cannabis cultivation has some advantages that are linked to its criminal character: indoor systems can be much better hidden from the police because they are invisible from the outside, whereas the typical cannabis odour can also be filtered. The intense cannabis odour is caused by typical biogenic volatile organic compound (BVOC) emissions. The latter are terpenes of which the most important is *β*-caryophyllene (Gertsch *et al*., 2008). Others include limonene, myrcene and the terpenoid linalool. The most important biological function is to repel insects. Although highly potent plants (i.e. with high THC-levels) also tend to contain high terpene levels, there is no direct physiological link between both types of molecules. Removing the odour is only done to prevent the plantation from being discovered as the smell is very intense.

Presence of an indoor cannabis plantation can be suspected from i) heat that is released by high-power growth lamps, that can be detected with infrared sensors; ii) observation of specific material and/or waste transports to and from cannabis production sites; and/or iii) unusually high electricity bills of buildings where indoor cannabis is grown. However, the latter problem for the grower is frequently circumvented by tapping electricity from the grid before it comes to the meter so that electric power consumption remains undetected (Benny Van Camp, Judicial Commissioner of the Directorate of Crime against Persons; personal communication).

Although soil-based cannabis cultivation remains the most commonly applied growing method, indoor cannabis cultivation also relies on more sophisticated soilless plant support methods such as hydroponics. In the latter method, a substrate other than soil is applied and plant nutrition is completely provided through mineral fertilizer addition. Advantages of hydroponics in comparison with soil-based cannabis cultivation include alleged higher yields and a shorter growth cycle. Substrates commonly applied in cannabis hydroponics include rock wool, expanded clay pellets, coconut fibre, perlite and vermiculite. Hydroponics can be passive (i.e. with manual irrigation) or active (i.e. with automated irrigation cycles). They can further be open (i.e. unused irrigation water with nutrients is continuously drained) or closed (the nutrient solution is continuously recycled back into the system). In closed systems, the nutrient solution is more efficiently used. However, as a result of nutrient uptake by cannabis plants, the composition of the nutrient solution needs to be continuously adjusted by adding soluble, mineral fertilizers and/or by adjusting the solution's acidity to ensure adequate mineral solubility. Acidity of the nutrient solution should be regularly monitored by pH measurements. Adjustment of pH to optimum levels (see further) can be performed by adding acids (lower pH) or bases (increase pH) to the nutrient solution. The mineral content of a nutrient solution can be monitored by regular measurement of its electrical conductivity (EC).

Examples of closed, active hydroponics systems include i) ebb- and flow-systems, in which the substrate is regularly flooded with a nutrient solution for a short period and subsequently drained (Fig. 2.4.); ii) nutrient film technique (NFT) in which a thin layer (film) of nutrient solution is continuously running over the surface that

supports the substrate, so that nutrients are continuously supplied to the latter while simultaneously providing sufficient oxygen to the roots (Fig. 2.5.); and iii) 'aeroponics', in which no substrate is used and where the nutrient solution is sprayed on to the roots (Fig. 2.6).

Any other cannabis cultivation system is a variation on the aforementioned systems. Micro-scale growers often use so-called 'growth tents' (Fig. 2.7.) which have a ground surface of usually not more than 1 m² and in which desired environmental conditions are controlled just as would be the case in larger scale cannabis plantations. The advantage of such a tent is its compactness, which helps to conceal cannabis cultivation operations. A more sophisticated (but rather exceptional) alternative is the so-called 'cannabis carrousel' (Fig. 2.8), consisting of rows of cannabis plants that rotate around a central axis with lighting, in such a way that roots are continuously and successively dipped in a nutrient solution, situated at the carrousel bottom. Of all cannabis cultivation systems mentioned in this section, the carrousel uses light and space most efficiently.

Fig. 2.4. *Ebb- and flow-hydroponics cannabis cultivation system using both rockwool and expanded clay pellets as a substrate (Source: https://www.icmag.com/; last visit: 02 December 2013).*

Fig. 2.5. *Hydroponics cannabis cultivation system with nutrient film technique (Source: http://www.rollitup.org/hydroponics-aeroponics/18488-does-anyone-use-nutrient-film.html; last visit: 02 December 2013).*

Fig. 2.6. *Aeroponics cannabis cultivation system (Source: http://www.weedwatch.com/; last visit: 02 December 2013).*

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Fig. 2.7. *Cannabis growth tent (Source: www.growery.org/; last visit: 02 December 2013).*

Fig. 2.8. *Cannabis carrousel* (*Omega Garden ®*) *(Source: http://www.omegagarden.com/; last visit: 02 December 2013).*

2.3.2. Environmental factors

Adequate control of environmental conditions (temperature, relative humidity and light) in a cannabis growth room is of critical importance in obtaining a qualitative and sufficiently high amount of cannabis at harvest. Cannabis tolerates a temperature in the growth rooms that ranges between 15 and 29 °C. However, cannabis plants can survive short temperature shocks above and below the latter range. Optimum temperature for indoor cannabis cultivation is between 20 and 25 °C. Temperature is usually controlled by i) removing hot air produced by the high-power growth lamps; and/or ii) by heating systems (particularly during winter months in temperate areas), when lamps produce insufficient heat to reach the minimum temperature. Relative humidity (RH) is ideally kept between 40 and 80 % (Green, 2001). Adams (2007), however, recommends a narrower range (50 – 70 %). Higher cannabis yields are claimed to be produced by enriching the atmosphere with CO_2. The latter practice can be achieved by means of high-pressure CO_2 cylinders, CO_2-releasing heating systems, or common household methods such as placing a mixture of vinegar and baking powder (bicarbonate) in the growth room.

Since no sun light is available in indoor situations, photosynthesis can only be enabled by light provided by lamps designed specifically for plant production, hence called 'assimilation lamps' (Box 1). They should produce a luminous flux of at least 54,000 lumen (lm) per m². Using the internationally defined conversion factor of 683 lm per W, the latter implies an irradiance of 79 W per m². However, the conversion factor is only valid for monochromatic light at a wavelength of 555 nm. The human eye is most sensitive to light with the latter wavelength (green light) which also corresponds more or less with the average photosynthetically active radiation (PAR) spectrum (400 – 700 nm) (McCree, 1972). As a result, we will assume the factor of 683 lm per W is appropriate for converting light requirements in indoor cannabis cultivation from lm per m² to W per m². Nowadays, the recommended irradiance is achieved by state-of-the-art high pressure sodium or metal halide lamps of 400, 600 or even 1,000 W (Toonen *et al*., 2006). Optimum distance between plant tops and assimilation lamps is between 30 and 40 cm in case of 400 W lamps, and between 50 and 60 cm in case of 600 W lamps. As a result of plant elongation, lamp height should be continuously adjusted, particularly during the vegetative growth stage (see

further). Light reflection in the cultivation room will enhance photosynthesis and consequently yield of cannabis plants. Reflection can be promoted by covering walls, floors and ceilings with white plastic sheets or painting. However, in Belgian indoor cannabis plantations, the common practice is to cover the ground with pond liner and walls with light-reflecting and heat-insulating sheets (Benny Van Camp, Judicial Commissioner of the DCP; personal communication).

Box 1 - The influence of light intensity, direction and quality on plant development and production under artificial lighting

In commercial horticultural production, reduction in photosynthesis and assimilate production caused by decreasing daily natural light sums in autumn and winter is often compensated by artificial lighting provided by so-called assimilation lights (van Ieperen, 2012). Indoor cannabis cultivation usually relies entirely on artificial lighting because growers try to conceal their activities as much as possible and consequently keep it far away from sources of daylight that might enable an outsider's view on the plantation.

Light is crucial for plants because it enables photosynthesis, which plays a key role in plant metabolism. Photosynthesis is the process in which plant leaves capture light through a large array of chloroplasts that enable carbohydrate synthesis from CO_2 that enters through the leaf pores (stomata). Leaves appear green in white light because chlorophyll absorbs light more efficiently in the blue and the red than in the green portions of the light spectrum (Lambers *et al*., 2008). Several studies (Eisinger *et al*., 2003; Meidner, 1968; Talbott *et al*., 2003; Savvides *et al*., 2012) further show that both instantaneous light quality and light quality during leaf development influence stomatal conductance for gas exchange. As a result, in indoor conditions, photosynthetic efficiency as well as transpiration will greatly depend on the spectral composition of assimilation lamps. Apart from that, light quantity, direction and diurnal duration regulate photosynthesis as well as processes such as germination, seedling establishment, plant architecture and transition to reproduction (van Ieperen, 2012).

The so-called 'shade-avoidance' plant response to changing light spectra and/or intensities illustrates the interaction between the earlier described light-mediated plant development (photomorphogenesis) and photosynthesis. When plants are subjected to shade (by other plants), many species will start to elongate internodes and leaf petioles in an attempt to bring the leaves out of the shade, thus enhancing photosynthesis (Franklin & Whitelam, 2005). The latter elongation is caused by a lower red/far red ratio in the light spectrum under shade (leaf absorption of red light is lower than that of far red light). The far red light thus strengthens apical dominance and reduces branching. Moreover, a far red rich light environment can cause acceleration of flowering, reduced storage of assimilates and shortened fruit development (Whitelam and Halliday, 2007). In indoor cannabis plantations, different plant densities will thus have different effects on the light quantity and quality available at plant level, which consequently will influence plant growth and flower bud development and yield.

Hot air and the intense cannabis odour, which is produced particularly during flowering, are usually removed by means of turbines. Air, evacuated from illicit indoor cannabis plantations is always passed through a carbon filter that absorbs most odour particles. Inside the growth rooms, air is usually internally circulated by ventilators that should be positioned perpendicularly to the flux of the air removed by the turbines so that all corners of the growth room receive some wind. Air circulation inside growth rooms enhances vigour of cannabis stems and homogenizes temperatures in the growth room.

2.3.3. Indoor cannabis growth cycles

In optimum indoor environmental conditions (see § 2.3.2.), most cannabis varieties, starting from rooted cuttings, will be ready for harvest in 8 to 11 weeks (i.e. one growth cycle). As a result, in a single growth room, up to 5 harvests can be achieved per year. Each growth cycle consists of 2 stages. During the first 2 to 4 weeks (vegetative stage), light is provided during 18 hours or longer per day, so that young plantlets quickly gain height and produce side branches with leaves. During the remaining weeks of the growth cycle (flowering stage), the light regime is reduced to 12 hours per day, which creates an artificial autumn that induces flowering. It is of critical importance that the dark period is not interrupted during the flowering stage, as this can postpone flowering and induce prevalence of monoecious plants (i.e. plants that bear both male and female flowers).

Except in the case of micro-scale cannabis cultivation, cannabis growth cycles typically depart from cuttings that were taken from mature, vegetative, female cannabis plants. Production of cuttings is usually done be specialized growers who supply a broad network of illicit cannabis growers. Seed dormancy seldom occurs in cannabis, but can easily be broken by scarification (i.e. a deliberate damage to the seed coat that enables water uptake by the seed, which is required for germination). Germination can take between 12 hours and three weeks. However, this is of little concern to illicit growers as they will mostly purchase rooted cuttings from a grower whose business is solely to produce and sell cuttings.

Cuttings are top or stem cuttings. They need to have at least two nodes, and are consequently between 10 and 15 cm long. Plant hormones (auxins), applied to the cutting wound, can stimulate root production. First roots occur after 5 to 14 days. During this stage, RH in the growth room should be 100 % and leaf surface should be reduced (by cutting part of the leaves) in order to reduce moisture loss through transpiration. Cuttings can be rooted in any substrate: peat soil, rock wool, sand, etc. Cannabis cuttings rooted in rock wool blocks are most commonly found in illicit indoor cannabis plantations in Belgium (Van Camp, 2008).

Toonen *et al*. (2006) studied plant densities reported from 77 confiscated cannabis plantations in The Netherlands. Most plantations (80 %) had a density of between 10 and 30 plants per m², with median plant density at 15 plants per m². In one occasion, 55 plants per m² were reported. In the latter case, the grower most probably used the so-called 'sea-of-green' (SOG) method in which cannabis plant density is very high – 60 plants per m² according to Cervantes (2006) and even up to 110 plants per m², according to Green (2001). In the SOG method, the cuttings are almost immediately subjected to a 12 h light / 12 h dark regime so that plants remain small and immediately start producing flower buds. Cervantes (2006) and Green (2001) claim that yield per m² of SOG systems is lower than yield per m² of more conventional indoor cannabis cultivation methods, which probably explains why SOG is a rarity in the Belgian cannabis sector (Van Camp, 2008).

In soil-based indoor cannabis production, pots are filled with loamy sand, peat soil or a mixture of both. When cuttings are transplanted, often a root stimulator is added together with mineral fertilizers. Soil pH is ideally between 5.2 and 6.2, and should be adjusted if needed. Growshops often supply fertilizer packages that have to be applied according to a schedule in which fertilizer composition and amounts vary per week, depending on the cannabis plant growth stage. An overview of such schedules with products available at Dutch growshops can be found at http://www.growcenter-noord.nl/ (last visit: 02 December 2013). However, each of the cultivation schedules basically include NPK fertilization (e.g. 20:20:20) complemented with Mg, Ca, S and micronutrients during the vegetative stage, and extra K, and especially extra P, during the flowering stage. Many growth schedules also recommend the application of numerous additives that are claimed to enhance yield

and quality of the harvested cannabis flower buds. The precise composition of these products is usually not mentioned on the product labels, so that their effectiveness is questionable. During the last 1 to 2 weeks of the flowering stage, it is recommended not to add any fertilizers in order to optimize cannabis quality. However, manuals are not clear on what is exactly meant with 'quality optimization', so that the supposed effect of nutrient deprivation in the last two weeks of the cannabis growth cycle is unclear.

Just as with soil-based cannabis cultivation, growshops provide fertilizer schedules for hydroponics as well. EC and pH of the nutrient solution are critical factors in cannabis hydroponics and both need to be continuously monitored, particularly in closed hydroponics systems. The pH of the nutrient solution is ideally between 5.2 and 6.3, whereas optimum EC values are in the range of 0.8 and 1 S/m in the vegetative stage, and between 1.2 and 2 S/m in the flowering stage. However, each individual cannabis growth schedule recommends specific optimum pH and EC values for each of the growth cycle.

Pruning is normally not required and completely advised against during the flowering stage, as it will reduce yield because developing flower buds will inevitably be removed. In some cases – particularly when low plant densities are applied (< 12 per m^2) – plants can be pruned to remove apical dominance so that side shoot formation is stimulated.

Duration of one cannabis growth cycle is usually between 8 and 11 weeks, depending on environmental factors, variety and the cultivation system used. Growth cycle duration will also depend on the grower's professionalism and experience. Rather than predefining a certain growth cycle duration as a function of methods used, growers should determine harvest time by visually evaluating cannabis flower bud ripeness. At least one third of the pistils should have turned orange or brown before harvest. The most commonly applied harvest method consists of cutting the main stem, close to substrate level, followed by clipping (i.e. separating flower buds from stem and leaves) and drying of cannabis buds. However, plants can also be hung upside down for drying prior to cutting. RH in the drying area should not exceed

80 % to avoid contamination of the flower buds with micro-organisms (fungi, bacteria).

Drying of cannabis (known as curing) should be a slow process because psychoactive (cannabinoids content) and organoleptic (taste, aroma and colour) cannabis properties gradually improve during drying. During this post-harvest period, cannabinoid acids decarboxylate into psychoactive cannabinoids whereas terpenes isomerise to create new polyterpenes with tastes and aromas that are different from fresh floral clusters (Clarke, 1981). In addition, conversion of carbohydrates and pigments modifies the final taste and colour of the plant material (Rosenthal, 1998). If drying occurs too rapidly, the metabolic processes responsible for the above-mentioned biochemical reactions are stopped too early. This in turn can result in an unpleasant “green” taste and notably modified colour of the product. Because it is suspected that cannabinoid biosynthesis may continue for a short time after harvest (Clarke, 1981), the drying process can also influence the final content of psychoactive constituents. It can nevertheless also be assumed that excessively dried flower buds weigh less and consequently are less profitable to the grower.

2.4. Criminal economy of cannabis cultivation

Decorte (2010a, 2010b) states that small-scale cannabis production should be considered as a specific segment of the Belgian cannabis market because he found that small-scale growers i) prefer a milder and more organic product than the cannabis sold through mainstream coffeeshop channels; and ii) are ideologically oriented growers that cultivate cannabis as part of a social subculture; as a result, they do not want to contribute to profits of criminal networks. Decorte (2010b) makes a case for government-regulated production and trade of cannabis that would limit possibilities for organized crime in the cannabis value chain. However, although some countries or regions have legalized or now tolerate cannabis cultivation and use (e.g. the tolerance policy in The Netherlands (Pakes & Silverstone, 2012); the recent legalization in Uruguay (The Economist, 2013); and the recent quasi-legalization in the states of Colorado and Washington, USA (Hawken *et al*., 2013)), in most countries, cannabis cultivation and trade today remain illegal activities. The economy of cannabis production and trade deviates from that of normal (legal) value chains because of specific costs and risk-affected profits linked with its criminal nature.

Becker (1968) performed the first economic analysis of criminal activity in general. He followed the usual economic assumption that a person commits an offence if the expected utility to her/him exceeds the utility she/he could obtain by using her/his time and other resources for other activities. Criminal utility can be derived from monetary or psychic gains resulting from crime. Offenders further face costs that are crime-specific: i) material costs (equipment, guns, vehicles, etc.); ii) psychic costs (guilt, anxiety, fear, dislike or risk); iii) expected punishment costs (including formal sanctions such as fines and incarceration, as well as informal sanctions such as inconveniences connected with arrest, law suit and conviction); and iv) opportunity costs (i.e. the net benefit of the legal activity forgone while planning, performing and concealing the criminal act) (Eide, 2000). Becker (1968) states that society can reduce the number of offences by increasing expected punishment costs for the offender. The latter is more effectively achieved by increasing overall probability that an offence is cleared by conviction rather than by

increasing the level of financial punishment per offence. In an economic analysis of drug selling gangs in the United States, Levitt & Venkatesh (2000) formulated similar conclusions. Eide (2000) nevertheless claims that economists tend to put too much emphasis on the rational choice theory that states that individuals always choose the course of action that best satisfies their expectations. The individual's norms and wants play an equally important role in criminal behaviour. Both are determined by personal characteristics such as age, gender or intelligence, as well as by societal features such as education, family situation, income level, etc. (Eide, 2000).

Easton (2004) used the assumption by Becker (1968) that the probability of being convicted is a major factor in calculating the cost of pursuing criminal activity. As a result, calculation of rates of return on costs (ROC), usually defined as net profit (sales minus total costs) divided by total costs, needs to be adjusted for the risk of getting arrested and/or convicted. If the probability of being convicted is π, then the cannabis grower has a probability of (1 – π) to sell a quantity of cannabis Q at unit price P. Following Easton (2004), ROC can then be calculated as

$$\text{ROC} = \frac{(1-\pi)PQ - C}{C} \qquad (2.1),$$

in which C is total monetary cost of cannabis growing (including opportunity costs), whereas P and Q the price and quantity of cannabis sales, respectively.

Calculation of ROC of cannabis growing thus requires knowledge on the value of π. The latter can be expressed as the ratio of the total number of confiscated plantations (B) and the total number of plantations (T) in a given region. However, estimation of a value for T is troublesome due to the rapidly changing situation both in terms of total plantation numbers as well as in terms of drug enforcement. Based on web surveys with 1,298 Finnish and 565 Danish cannabis growers, Hakkarainen *et al*. (2011) found that the perception of risk of arrest is significantly ($p < 0.05$) higher in Finland than in Denmark. In Quebec (Canada), π values of 0.05 (Bouchard, 2007) and 0.10 (Bouchard, 2008) are reported, whereas Easton (2004) assumes 0.16 is a good estimate for π in British Columbia (Canada).

Easton (2004) further states that ROC of cannabis growth operations should be in equilibrium with legal market ROC values (further referred to as ROC*) because differences between ROC and ROC* would normally attract people to, or pull them back from the cannabis sector depending on which is highest. ROC of cannabis growing is nevertheless higher than ROC* because of the risk factor that comes with illegal activities. If one were loaning funds to a cannabis producer, the lender may insist on a risk premium associated with the loan so that the constraint associated with an equilibrium in the cannabis growing business is not the market return (ROC*), but a return that is risk-adjusted above those associated with legal investments. Easton (2004) therefore shows ROC of cannabis growing to be $(ROC^* + \pi) / (1 - \pi)$.

We continue with outlining some micro-economic aspects of indoor cannabis plantations. Based on police data from 3,212 cannabis plantation seizures and interviews with 31 cannabis growers in Quebec (Canada), Bouchard (2008) found a significant correlation ($R^2 = 0.88$, $p < 0.001$) between the number of plants and the number of co-offenders in any given indoor cannabis plantation. As with legal economic activities, economies of scale also prevail in cannabis production. The latter means that increasing the scale of cannabis cultivation reduces the cost per unit of production because large-scale production systems are able to use resources more efficiently. Hydroponics-based cannabis cultivation, however, was found to profit relatively more from economies of scale than soil-based cannabis cultivation, because, once installed, the first cultivation system functions almost entirely automatically (Bouchard, 2008).

Approximately half of cannabis plantations seized in Belgium contain less than 50 plants (see § 1.1. and Fig. 1.1.), indicating that illicit cannabis growers in Belgium not necessarily are looking for the highest economies of scale. Hammersvik *et al*. (2012) explain the mechanisms that prevent small-scale cannabis growers to increase their scale of operation by the reasoning that large-scale cannabis growing requires i) higher levels of organizational skills which consequently increases risk of being detected; ii) a larger and usually unavailable amount of financial investment in comparison with small-scale plantations; iii) access to illegal distribution networks and thorough knowledge of black market norms and structures; iv) advanced horticultural skills; and v) abandonment of anti-commercial, anti-violence, ecological

and community values, often linked to small-scale cannabis growing (see also Decorte 2010a, 2010b).

Scientific estimates on investment and operational costs of indoor cannabis production are scarce. Cervantes (2006) reported total costs of two real-case Dutch cannabis indoor plantations to be € 356 per m² for a 12 m² plantation, and € 492 per m² for a 24 m² plantation. Caulkins (2010) estimated total costs of three typical (sic) cannabis plantation sizes in the United States. Cost estimates were € 988 per m² for a small-scale (2.3 m²) plantation; between € 904 and € 1,808 per m² for a mid-scale plantation (140 m²); and between € 158 and € 486 per m² for an industrial plantation (4,000 m²) (all prices in this section were converted from US$ using a conversion factor of 0.75). According to Caulkins (2010), the lower costs mentioned by Cervantes (2006) are probably linked to the location of the studied plantations in the Netherlands, where cannabis growing infrastructure and consumables are more easily and abundantly available.

The price fixing mechanism of drug markets in general (Caulkins, 2007) has some specific characteristics: i) just as in conventional markets, quantity discounts (i.e. higher quantities are sold at a lower price) prevail in drug markets, whereby the discount is more substantial in the latter markets (Box 2); ii) due to the lack of official standards and control mechanisms, illicit drugs are of highly varying quality, which has a high impact on drug prices (e.g. lower prices for cannabis grit and cannabis with much leaf and stem material as compared to full, clean flower buds); iii) substantial spatial variation prevails in drug prices across countries as well as within a country between cities. As a result of these highly variable prices, farm-gate price reports exhibit a wide range. Hammersvik *et al*. (2012), for example, report farm-gate prices of between € 13 and € 16 per g of dried cannabis buds, which is higher than the most recent retail price range mentioned for the European cannabis market (€ 8 - € 12 per g, interquartile range) (EMCDDA, 2013b). Supposedly, high demand in relation to low supply in Norway, as well as a general high level of consumer prices in comparison with EU countries, are responsible for these high farm-gate prices (Hammersvik *et al*., 2012). In British Columbia, where supply in relation to demand is much higher than in Norway, farm-gate prices of just $ 3.5 (€ 2.5) per g are reported for the year 2003 (Plecas *et al*., 2005). The latter price is probably so low because it

applies only to quantities > 1 kg. Sound comparison of different reported farm-gate data is also hampered by the different periods in which price data were gathered, because cannabis prices tend to evolve with time as well (Caulkins, 2007).

Box 2 - Quantity discounts and mark-ups in cannabis markets

Just as for licit products, mark-ups and quantity discounts prevail in drug markets. Mark-ups imply that the farther one moves down into the value chain (from producer to consumer), the higher the unit price of a product becomes (Caulkins, 1994). Opposed to this, lower unit prices at higher levels of the value chain are referred to as quantity discounts. In legal value chains, quantity discounts occur as a result of economies of scale, meaning that larger transaction volumes are traded more efficiently. In this case, the discount does not exist per se but rather reflects a fixed cost per transaction, independent of transaction size. Total price (*P*) could then be expressed as

$$P = a + bQ \quad (2.2),$$

in which *Q* is transaction size, *a* is fixed transaction cost and *b* the constant unit price. However, based on correlation analysis of cannabis price and quantity data from the United States, Caulkins & Padman (1993) rejected the fixed cost model. Instead, they showed that data much better fit a log-linear model of cannabis price as a function of transaction size. The latter model is derived from the assumption of a hierarchical domestic distribution network in which a dealer at a certain level buys a quantity of cannabis, repackages the drugs into Φ equal size units (branching factor) and sells them at a multiple δ of the original price. If it is assumed that Φ and δ are the same at every level of the value chain, it can be shown that

$$P(Q) = \alpha Q^{\beta} \quad (2.3),$$

in which *P(Q)* is the price for an amount *Q* in a drugs transaction, $\beta = 1 - \ln(\delta)/\ln(\Phi)$ and α is a constant (for details, see Caulkins & Padman, 1993; Clements, 2006). When $\delta > 1$, then $\beta < 1$, which implies that prices will increase less than proportionally with size. Size elasticity of price is thus expressed by β, whereas discount elasticity is $\beta' = 1 - \beta$.

Values reported for discount elasticity β' in cannabis markets are -0.24 in Australia (Clements, 2006), -0.23 in the United States (Caulkins & Pacula, 2006; Caulkins & Padman, 1993) and -0.19 in New Zealand (Wilkins *et al*., 2005). Mark-ups in drug markets are more considerable than in licit markets because the higher branching factor Φ (i.e. the number of sales by a dealer at level x), the higher the risk of being detected by enforcement agents (Caulkins, 1997). The risk factor increases transaction costs, which is reflected in the multiplier δ and ultimately in the price (Caulkins & Padman, 1993). One implication of the substantial mark-ups (or quantity discounts) to go with cannabis marketing is that reporting the so-called 'street' (i.e. retail) value of confiscated drugs considerably biases their true market value which, in most cases, is significantly lower (Caulkins, 1994; Caulkins & Padman, 1993).

CHAPTER 3 Factors determining yield and quality of indoor cannabis cultivation

Adapted from:

Vanhove, W., Van Damme, P. & Meert, N. (2011). Factors determining yield and quality of illicit indoor cannabis (*Cannabis* spp.) production. Forensic Science International, 212(1-3), 158-163.

3.1. Introduction

Recent seizures of Belgian indoor plantations revealed that cannabis cultivation has become increasingly sophisticated, using automated lighting, ventilation and irrigation systems, and fertilization packages that follow technical growth schedules obtained from Dutch growshops (Van Camp, 2009). As a result, the Belgian Police has observed cannabis plants in seized plantations with yields that visually seems to be far above the estimate of Toonen *et al*. (2006), which was set at 28.1 g of dry female flower buds per plant (lower bound of the one-sided 95 % confidence interval). In order to update this yield figure, we needed to address the shortcomings of the latter research, i.e. i) cannabis yield was not estimated by actually growing cannabis plants in a scientific experimental set-up, but was predicted by linear regression using plant density, light intensity and flower maturity stage of plants from 77 confiscated plantations as explanatory variables; and ii) Toonen *et al*. (2006) did not account for yield variability between the different cannabis strains that prevail on the Dutch cannabis market. In this chapter, we will analyze the effect of important cannabis cultivation factors (plant density, light intensity, variety and plant nutrition) on cannabis yield and quality.

Although some growers use hydroponics in cannabis cultivation, the present chapter will mainly focus on peat soil cultivation, which is the most common indoor cannabis production system in Belgium. The aims of this chapter are to i) assess which are the most important yield-determining factors in indoor cannabis cultivation; ii) evaluate which of the yield determining factors also affect cannabinoid concentrations; and iii) assess whether cannabinoid concentrations obtained through current variety x growth conditions, correspond with values previously reported in The Netherlands (Rigter & Niesinck, 2010).

3.2. Material and methods

Indoor cannabis yield- and quality-determining factors were studied in two separate experimental growth cycles. In the first cycle (11 weeks; 20 May 2010 – 30 July 2010), the influence and the interaction effects of three main growth parameters (plant density, light intensity and variety) were investigated (for details see § 3.2.1). The second cycle (14 weeks; 30 September – 30 December 2010) consisted of two experiments: i) evaluation of the influence on yield of lower plant densities than the ones used in the first cycle; and ii) assessment of the effect of reducing the recommended nutrient application to a basic level (i.e. the lowest levels of NPK fertilizers without adding other plant stimulating substances that are recommended in most common growth schedules) whereby also considering its interaction with the variety factor (for details see § 3.2.2). The last experiment will verify the potential claim by a cannabis grower's defence in court that fertilizers used by these growers were not applied according to the standard schedules, with a significant negative impact on cannabis yield as a result.

3.2.1. Cycle 1: influence of plant density, light intensity and variety

3.2.1.1. Experimental design

Toonen *et al*. (2006) evaluated the frequency of plant densities that prevailed in the 77 confiscated growth rooms that formed the basis for their study. Eighty % of growth rooms contained densities between 10 and 30 plants per m². Average density was 15 plants per m². In our experimental growth cycle, we applied two plant densities: 16 and 20 plants per m², corresponding to 43 % of plantations in the 9-16 plants per m² interval and 29 % of plantations in the 17-24 plants per m^2 interval, respectively, that were reported by Toonen *et al*. (2006). It should be stressed that the 'plant density' factor in our experiment can not be strictly interpreted because the effect of the factor is confounded by both pot volume and pot shape (Lemaire & Morel, 2003) which differ across different plant 'densities' as applied in our experiment (see § 3.2.1.2).

Overhead lights should provide at least 54,000 lumens (lm) per m² (i.e. 79 W per m² at 555 nm; see § 2.3.2) (Adams, 2007; Green, 2001). Nowadays, such light intensities are achieved by high-pressure sodium (HPS) or metal halide (HPI) lamps of either 400 W or 600 W (Toonen *et al*., 2006). Lamps of both wattages are most commonly found in Belgian indoor cannabis plantations (Benny Van Camp, Judicial Commissioner of the Directorate of Crime against Persons; personal communication). As a result, both light intensities were used as a treatment in this study.

The experiment was conducted in a secured square growth room with sides of 5.5 m and a height of 2.4 m. It consisted of three yield determining factors that were combined in a full factorial split-plot design: i) light intensity (400 W per m² and 600 W per m²); plant density (16 and 20 plants per m²); and ii) variety (Super Skunk, Northern Light #5 x Haze, White Widow and Big Bud). The latter cannabis varieties were selected for our experiments because of i) their apparent popularity in coffeeshops and with seed suppliers (information derived from internet websites) and ii) the availability of feminized seeds of these varieties in Amsterdam cannabis growth shops (see § 3.2.1.2. for details).

Plant densities were randomly assigned to two whole plots of 8 m². Within each whole plot, the light intensities were randomly assigned to two split-plots of 4 m² each. In order to avoid influence of the factor combinations applied to each of the 4 split-plots thus obtained, they were separated by a corridor of 1 m wide. Each whole plot / split-plot combination was further divided in 4 split-split-plots, each containing a different cannabis variety. A total of sixteen square experimental subplots (1 m²) were thus obtained, each containing 16 or 20 plants per m² and receiving light from one 400 W or 600 W lamp. Subplots with cannabis varieties were positioned in such a way that the complete experimental design formed a Latin square (Fig. 3.1).

A split-plot design is often used in agronomic experiments where one or more factors (e.g. soil texture or irrigation) can not be spatially randomized (so-called hard-to-change factors) (Jones & Nachtsheim, 2009). Complete randomization of factor combinations (i.e. randomly spatial distribution of each of the three factor

combinations) was not possible because i) a lamp with a given power and spectral distribution in a subplot adjacent to another subplot with different power and spectral distribution will excessively influence development and yield in the latter subplot; and ii) mixing subplots with different plant densities will similarly influence yield and development of plants in neighbouring subplots because of different plant architecture that might influence light interception in neighbouring subplots.

3.2.1.2. Preparation

Cannabis varieties (also called 'strains') were purchased in packages of 10 seeds per variety from growshops in Amsterdam (the Netherlands). Varieties 'Super Skunk', 'Northern Light #5 x Haze' and 'Big Bud' were obtained from the 'Sensi Seed Bank', a renowned cannabis seed bank and cannabis breeder. The 'White Widow' variety was bought in the FantaSeeds growshop. Since only female plants produce cannabis buds (containing highest concentrations of the psychoactive cannabinoids when compared to male flowers), it was important to have only female plants in the experimental blocks. To this aim, only so-called ‘feminized’ seeds were bought. Indeed, during the experiment no male plants were reported.

Seeds (10 per variety) were sown in peat soil on February 4th 2010 in a nursery at the greenhouse in the Faculty of Bioscience Engineering, Ghent University. Seed plants (10 per variety) were propagated by means of stem cuttings that were taken successively on March 3rd and March 24th 2010. Rooting of cuttings was stimulated by dipping each cutting in Rhizopon A™ powder (indole-3-acetic acid), as described by Arteca (1996). Cuttings were taken in equal amounts from each mother plant and subsequently randomly mixed so that each variety subplot contained a random mixture of clones from the 10 original seedlings of the respective variety. Cuttings were placed in rock wool cubes on a heated greenhouse table and covered with plastic in the greenhouse nursery (Fig. 3.4) until they were sufficiently rooted (i.e. after between 2 and 3 weeks). Cuttings with rock wool cubes were subsequently transplanted in pots (diameter: 0.2 m) filled with peat soil in order to grow parent plants (15 per variety) that were placed under 600 W lamps that provided 18 h light per day, in a growth room adjacent to the experimental growth room (Fig. 3.5). On 30 April 2010, 150 stem cuttings per variety were taken from these plants using the

same methodology as described above. The experiment thus consisted of a random mixture of clones from 10 original plants per variety. Rooted cuttings were transplanted in pots in the experimental room on May 20th. Plants were placed on the ground either in round pots (diameter 0.22 m) of 5 L (in blocks of 20 plants per m²) or in square pots (sides 0.25 m) of 11 L (in blocks of 16 plants per m²) (Fig. 3.6). Lamps were positioned above the centre of each subplot of 1 m². Lamp height was 40 cm and 60 cm above plant tops for 400 W and 600 W lamps, respectively. Pots were filled with peat soil (pH 6.4, OM: 20 %) that was mixed with 5 % perlite (obtained from Snebbout N.V., Kaprijke).

600 W 16/m² SS	600 W 16/m² WW	400 W 20/m² BB	400 W 20/m² NL
600 W 16/m² NL	600 W 16/m² BB	400 W 20/m² WW	400 W 20/m² SS
400 W 16/m² WW	400 W 16/m² SS	600 W 20/m² NL	600 W 20/m² BB
400 W 16/m² BB	400 W 16/m² NL	600 W 20/m² SS	600 W 20/m² WW

Fig. 3.1. *Experimental full factorial split-split-plot design of the first cannabis cultivation cycle with light intensity (600 W and 400 W lamps) as well as plant densities (16 and 20 per m²) in whole plots; and varieties (SS = Super Skunk, WW = White Widow, NL = Northern Light #5 x Haze, BB = Big Bud) in subplots.*

3.2.1.3. Nutrition

Cannabis plants were uniformly treated with fertilizers that were added to the irrigation water. Fertilization and light regime were applied according to the *Canna Terra* growth schedule (except for the application of root stimulator Growstar ® 'Gold Excelerator') that - according to Belgian federal police - is frequently applied in illicit

cannabis cultivation (Table 3.1). The schedule was found at http://www.onlinegrowsupplies.com/CANNA_Terra_kweekschema.pdf (last visit: 02 December 2013). Fertilizers and other additives were obtained from illicit plantations that were confiscated by the Belgian federal police. Terra Vega™ (NPK 3-1-4) and Terra Flores™ (NPK 2-2-4) fertilizers stimulate vegetative growth and flowering, respectively. Growstar ® Gold Excelerator™ is a root stimulator in which auxins (no further specification) are active components. Cannazym™ is, according to the label, an enzyme mixture (not specified) which is claimed to enhance mineralization of organic soil material, such as dead roots. Cannaboost™ is advertised on its label as an additive which improves photosynthesis. Although some websites claim that the active substance in Cannaboost™ is the natural growth stimulant triacontanol ($CH_3(CH2)_{28}CHOH$) (Box 3), no reliable information on the composition of Cannaboost™ was found. PK13/14™ (NPK 0-13-14) is added during one week in the middle of the flowering stage in order to support intensive flowering in that period. Irrigation water was applied every two days in amounts that were arbitrarily, and visually determined on the basis of supposed plant requirements.

Table 3.1. *Fertilizer growth stimulator schedule applied in the cannabis cultivation experiment (first cycle), based on the* Canna Terra *growth schedule*.

Week	Light h/day	Terra Vega ml/10L	Terra Flores* ml/10L	Gold Excelerator † ml/10L	Cannazym* ml/10L	Cannaboost* ml/10L	PK 13/14* ml/10L
20 - 21	18	20	-	40	-	-	-
22 – 23	18	40	-	15	25	-	-
24	12	-	60	5	25	30	-
25	12	-	55	5	25	30	15
26 – 28	12	-	60	5	25	30	-
29 - 30	12	-	-	-	25	30	-

** Product of the brand Canna ®; † product of the brand Growstar ®. Weeks are calendar weeks of 2010.*

- Product was not applied.

Box 3 - Triacontanol

Triacontanol ($CH_3(CH2)_{28}CHOH$) is a 30-carbon, straight-chain primary alcohol (Houtz *et al*., 1985).It was first identified by Chibnall *et al*. (1933) as a natural component of epicuticular waxes in *Medicago sativa* (alfalfa) (Tantos *et al*., 1999). Decades later, Ries *et al*. (1977) discovered that when coarsely chopped alfalfa applied as a soil amendment, significantly increased yield of tomato (*Solanum lycopersicum* L.), cucumber (*Cucumis sativa* L.) and lettuce (*Lactuca sativa* L.) in comparison with control, whereby triacontanol from the alfalfa cuticle was the main plant growth-promoting component. Foliar and soil application (usually as a stable colloidal dispersion particles in water) of triacontanol concentrations as low as 0.5 – 20 µg per l were shown to have a positive effect on i) levels of reducing sugars, amino acids, soluble protein and nitrogen, and enzymatic activity in rice (*Oryza sativa* L.) and corn (*Zea mays* L.) seedlings (Laughlin *et al*., 1983; Naeem *et al*., 2012; Ries, 1984; Ries & Houtz, 1983); ii) yield of corn and tomato (Eriksen *et al*., 1982); iii) total chlorophyll content and photosynthetic CO_2 assimilation in the green algae *Chlamydomonas* sp. (Houtz *et al*., 1985); iv) phenol levels and nutrient uptake in *Vigna radiata* L. (Kumaravelu *et al*., 2000); v) nitrogen-fixation, enzymatic and photosynthetic activity, and crop productivity and quality of *Lablab purpurea* L. (Naeem *et al*., 2009); and vi) number of flowers in *Bougainvillea glabra* (Khandaker *et al*., 2013). It was furthermore shown that triacontanol enhances root and shoot formation in micropropagation of *Melissa officinalis* L. (Tantos *et al*., 1999), *Capsicum frutescens*, *Decalepis hamiltonii* (Reddy *et al*., 2002) and *Bupleurum fruticosum* (Fraternale *et al*., 2002). The substance induces direct somatic embryogenesis in *Coffea arabica* and *C. canephora* (Giridhar *et al*., 2004). Triacontanol also has a positive effect on the production of secondary metabolites: it enhances i) essential oil levels in lemon grass (*Cymbopogon flexuosus*) (Misra & Srivastava, 1991), *Thymus mastichina* (Fraternale *et al*., 2003), mint (*Mentha arvensis* L.) (Naeem *et al*., 2011), and ginger (*Zingiber officinale* Rosc.) (Sing *et al*., 2012); ii) artemisinin levels (used as a drug against malaria) in *Artemisia annua* L. (Shukla *et al*., 1992); iii) and opium and morphine levels in *Papaver somniferum* L. (Khan *et al*., 2007). Furthermore, some plant stress reducing properties of triacontanol were reported: *Erythrina variegata* is less affected by Cd^{2+}-toxicity when triacontanol is supplied to the growth medium (Muthuchelian *et al*., 2001), whereas the effectiveness of triacontanol to relieve the impact of saline conditions is less clear (Perveen *et al*., 2010; Shahbaz *et al*., 2013). The growth-promoting effect of triacontanol is declining at high concentrations (> 100 µg per l), as was shown in experiments on corn, potato (*Solanum tuberosum* L.) (Ries & Houtz, 1984) and ginger (Sing *et al*., 2012). Long-chain compounds such as morpholine, phtalate esters (Ries & Houtz, 1983) and octacosanol (Houtz *et al*., 1985) also inhibit the growth-promoting effects of triacontanol. It is still not fully understood how triacontanol physiologically affects plant growth parameters. Since triacontanol is ubiquitous (i.e. besides the cuticle, present in all plant parts of all plants), it is not considered a plant hormone because its action cannot be interrupted by removing a certain plant part (Ries, 1984; 1991; Ries & Houtz, 1983). Ries (1991) showed that triacontanol rapidly elicits a second messenger in rice which he identified as 9-*β*-L(+)-adenosine. The signalling pathway of triacontanol was not further revealed until Chen *et al*. (2002; 2003) discovered that triacontanol suppresses genes encoding for stress-related proteins and up-regulated genes expressing photosynthetic and photorespiratory proteins.

3.2.1.4. Environmental control

Total growth cycle duration was 11 weeks and consisted of a vegetative stage (first 4 weeks) in which light was provided during 18 hours per day and a flowering stage (subsequent 7 weeks) initiated by and with 12 hours of light and 12 hours of darkness. Switching lights from an 18 hours to a 12 hours light regime creates an artificial short-day period, inducing flowering in cannabis. Lamp height in each of the subplots was continuously adjusted so that lamps remained at 0.6 m above canopy level. Lamps of 400 W were Philips ® Master HPI-T Plus E40 1SL metal-halide lamps (41,000 lm). Lamps of 600 W were Philips ® Master SON-T PIA Plus E40 high-pressure sodium (HPS) lamps (90,000 lm). Spectral power distribution of lamps is shown in Fig. 3.2. Since plants remained visually healthy during the whole growth period, no pesticides were used. Plants that produced heavy apical female inflorescences were supported by means of bamboo sticks in order to avoid stem bending or even breaking. Temperature inside the growth room, measured on a daily basis by means of a minimum/maximum thermometer placed in the centre of the growth room at a height of 1.5 m above the ground, was kept below 30 °C (Fig. 3.3) by continuously removing hot air using a RoScro ® turbine with a maximum flow rate of 6,000 m³ per h. Turbine speed was controlled by a Torinsifan ® Regulation Intelligent Controller (RIC), functioning as a thermostat. Removed air was continuously filtered using a cylindrical carbon filter (brand unknown, height: 1 m, diameter: 0.44 m) in order to prevent the intense smell during flowering from leaving the room. Fresh air entered the room through a vent hole of 1.2 m x 0.8 m in the wall opposite the carbon filter. Air circulation inside the growth room was further enhanced by a Honeywell NV-1800E ventilator (flow rate: 6,100 m³ per h) that was placed in the middle of one of the side walls, perpendicular to the walls with carbon filter. All aforementioned equipment was obtained from a stock of confiscated cannabis production material, held by the Belgian federal police.

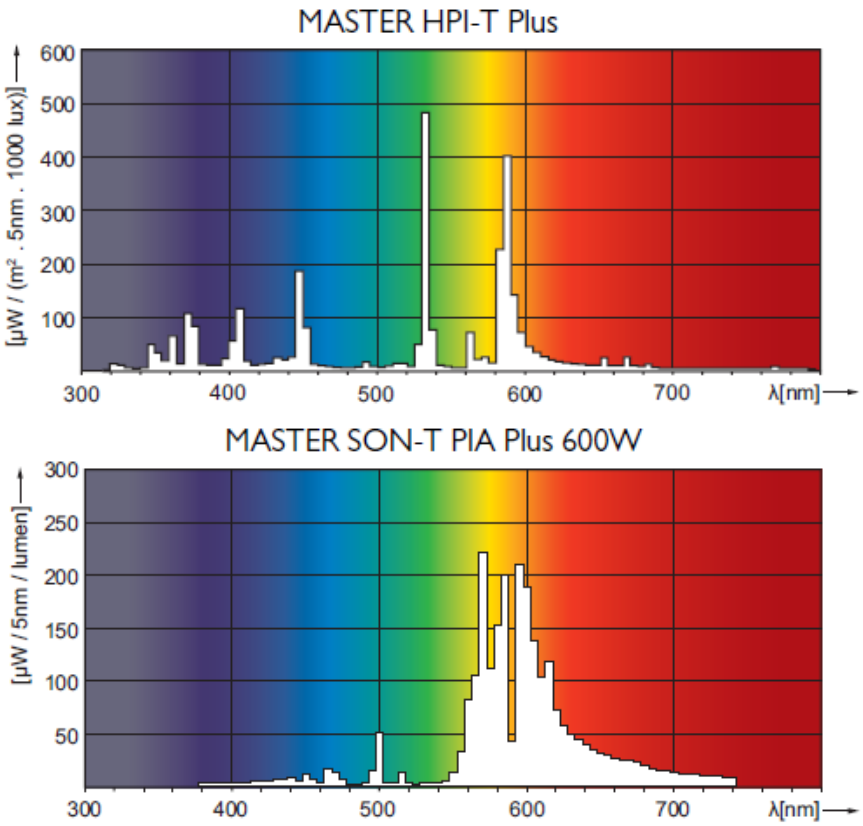


Fig. 3.2. *Spectral power distribution of the Philips ® Master HPI-T Plus E40 1SL metal-halide lamps (400 W) (above) and the Philips ® Master SON-T PIA Plus E40 high-pressure sodium (HPS) lamps (600 W) (below) used in cannabis growth experiments.*

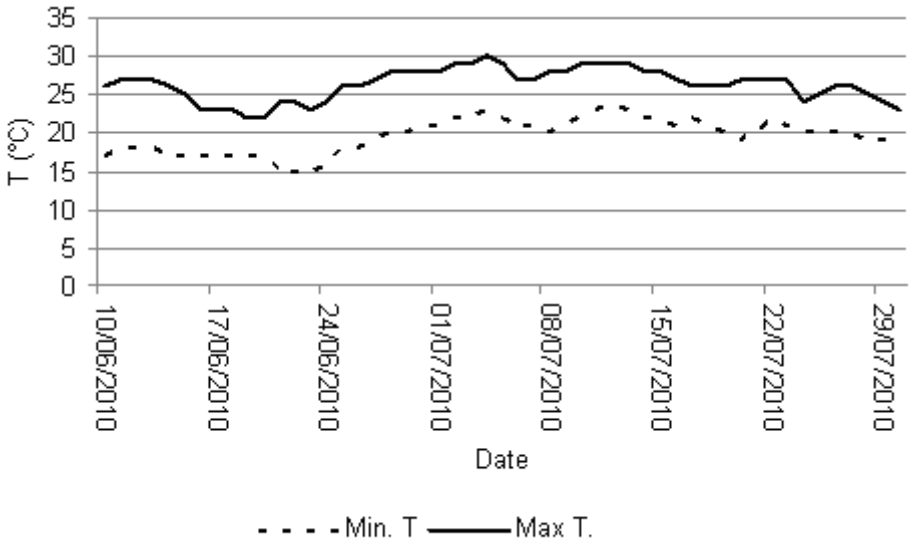


Fig. 3.3. *Daily measured minimum and maximum temperature in de growth room during the first growth cycle.*

Daily records of temperature during the growth cycle allow calculation of the growing degree days (GDD, i.e. a measure of heat accumulation in a growth cycle, calculated as the differences between the average of the daily maximum and minimum temperatures and a base temperature (usually 10 °C), accumulated for all days up to a certain point in the growth cycle (Yang *et al*., 1995)). We computed GDD using a base temperature of 10 °C for the whole cycle (i.e. from the moment rooted cuttings were placed in the growth room, up to the harvest).

3.2.1.5. Data collection and analysis

After 11 weeks (July 30th 2010), when pistils started turning brown (Fig. 3.7 – 3.9), plants were labelled and harvested. The main stem was cut at the bottom after which plants were hung upside down to dry in the dark during 10 days (Fig. 3.10). Subsequently, female inflorescences were separated from the plants using scissors and leaves between inflorescences manually clipped (Fig. 3.11). Flower buds were then put in paper bags together with the original plant label (Fig. 3.12). Finally, flowers harvested were weighed per plant using an OHAUS Adventurer ™ digital balance (precision: 1 mg). Yield per plant was converted to yield per m² by multiplying per plant yield by 16 and 20 in blocks with 16 and 20 plants per m², respectively.

Because of the presence of both split-plot and whole-plot random errors, split-split-plot designs can not be analyzed by ANOVA. The latter can only be used for completely randomized designs (Jones & Nachtsheim, 2009). Correct analysis involves removing the sums of squares and degrees of freedom for the whole-plot error from the error terms in the incorrect completely randomized analysis (Montgomery, 2012; Potcner & Kowalski, 2004). Since the experiment is just one block with no replicates, we added an artificial blocking factor with 4 levels to the data (i.e. each split-split-plot with 16 or 20 measurements was randomly divided in 4 parts ('blocks'); for each block thus obtained per split-split-plot, average yield per plant and average yield per m² were calculated). Analysis of variance was subsequently done using a nested model in the statistical software package R 3.0.1. Data exploration was done in SPSS 20. For multiple comparison of means between the four levels of the variety factor, the Least Significant Difference (LSD) was manually calculated

using the mean square errors obtained in the split-split-plot analysis of variance (see above). In case interactions between the variety factor and the other factors prevailed, multiple means comparison (with the LSD-method) between varieties was done also per light x density split-plot, as recommended by Gomez & Gomez (1984).

3.2.1.6. Analysis of cannabinoid concentrations

For each of the 16 factor combinations, a mixed sample of flower buds from 10 randomly chosen dried plants was taken. Reference materials Δ^9-tetrahydrocannabinol (THC), cannabinol and cannibidiol were purchased from Lipomed. Ethanol was purchased from Biosolve and tribenzylamine from Acros Organics. Identification and analysis of cannabis and cannabis products was based on recommendations by the United Nations Office on Drugs and Crime (UNODC, 2009). Homogenized plant material (20 – 30 mg) was extracted with 10 ml internal standard solution (0.5 mg/ml tribenzylamine in ethanol) for 10 minutes in an ultrasonic bath. Subsequently, samples were placed in a rotator for 30 minutes.

Gas chromatography mass spectrometry (GC-MS) analysis (HP6890N-5973N, Agilent Technologies) was performed for identification, which was based on comparison with reference materials and library spectra (PMW and NIST.08). Gas chromatography flame ionization detection (GC-FID) analysis was subsequently done for quantification, using HP6890 (Agilent Technologies). Separation was achieved on a HP 1 column (25 m x 0.32 mm I.D. x 0.52 µm film thickness; J & W Scientific, Agilent Technologies). Helium, the carrier gas, had a constant flow of 1.8 ml/min. One µl sample was injected with a split ratio of 25:1 at 275 °C. Oven temperature was programmed at 250°C (hold 9.50 min). Detector parameters were set at a temperature of 300°C, a hydrogen flow of 30 ml/min and an air flow of 400 ml/min. Chemstation software (Agilent Technologies) was used for data retrieval and calculations. Calibration was performed with cannabinol as reference material.

A substantial amount of THC in the plant material is present under the form of its precursor Δ^9-tetrahydrocannabinolic acid (THC-A) which is converted into the psychoactive THC when heated. THC thus forms by decarboxylation of THC-A when cannabis products are smoked. According to Dussy *et al*. (2005) and Wohlfarth *et al*.

(2011), only some 70% of THC-A is converted to THC during an optimized GC analysis, whereas full conversion of THC-A to THC during analysis is needed in order to correctly determine THC-concentration in the sample.

In order to check the conversion factor in the analyses of our study, some additional experiments were carried out. In one experiment, decarboxylation was performed prior to analysis, as proposed by UNODC (2009). A second analysis was done following the methods described here-above. Both analyses, with and without decarboxylation, resulted in similar THC concentrations. Based on these results, it can be assumed that the conversion from THC-A to THC is complete in our experiments. The lower conversion reported by Dussy *et al*. (2005) might be an artefact, caused by differences in injector geometry, as suggested also by UNODC (2009).

Statistical analysis was done in SPSS 20. Analysis of variance of cannabinoid concentrations could not be performed since per light x density x variety factor combination only one observation of each of the three considered cannabinoid concentrations was available. Instead, statistical differences in cannabinoid concentrations between main factors density and light were tested by means of a T-test, whereas ANOVA was used to test differences in cannabinoid concentrations between different varieties.

Fig. 3.4. *Cuttings in rock wool blocks, placed on a heated greenhouse table at the Faculty of Bioscience Engineering (Ghent University) (30 March 2010; i.e. 4 weeks after cutting, plastic removed).*

Fig. 3.5. *Parent plants cultivated in a separate growth room adjacent to the experimental growth room (27 April 2010). Cuttings were taken from these plants to obtain the plants used in experiments.*

Fig. 3.6. *Experimental growth room with 400 W lamps (far left) and 600 W lamps (near left) (picture taken on 2 July 2010, i.e. 6th week of the 11-week first growth cycle).*

Fig. 3.7. *Emergence of the first flowers (25 June 2010; 5th week of the first growth cycle).*

Fig. 3.8. *Mature flower bud of a Northern Light #5 x Haze plant in the 11th week of the first growth cycle (26 July 2010).*

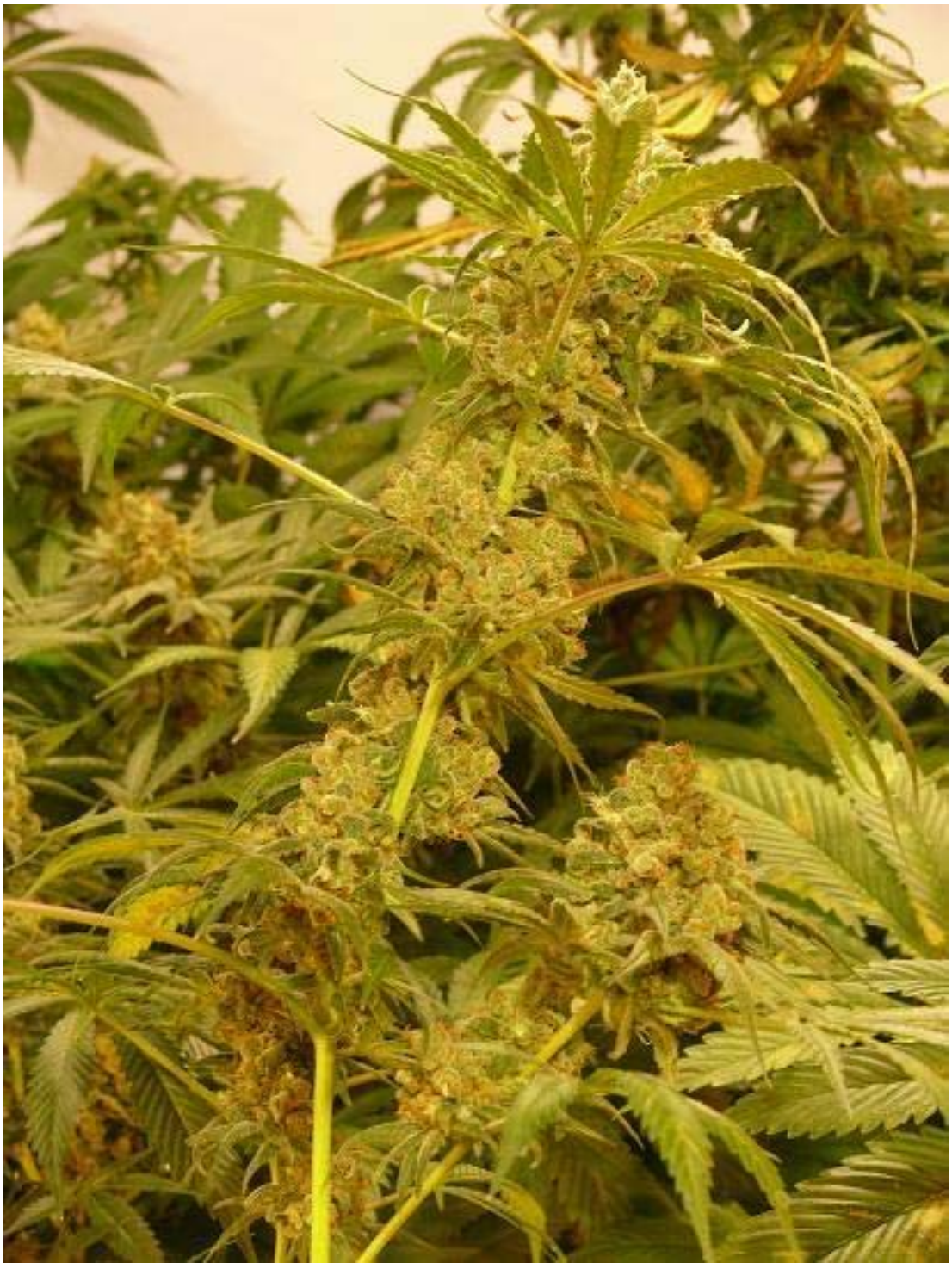


Fig. 3.9. *Mature cannabis plant of the Big Bud variety (26 July 2010; 11th week of the first growth cycle).*

Fig. 3.10. *Drying of harvested cannabis plants following the first growth cycle (06 August 2010).*

Fig. 3.11. *Clipping (removal of leaves that grow in between flower buds) of harvested and dried cannabis (17 August 2010).*

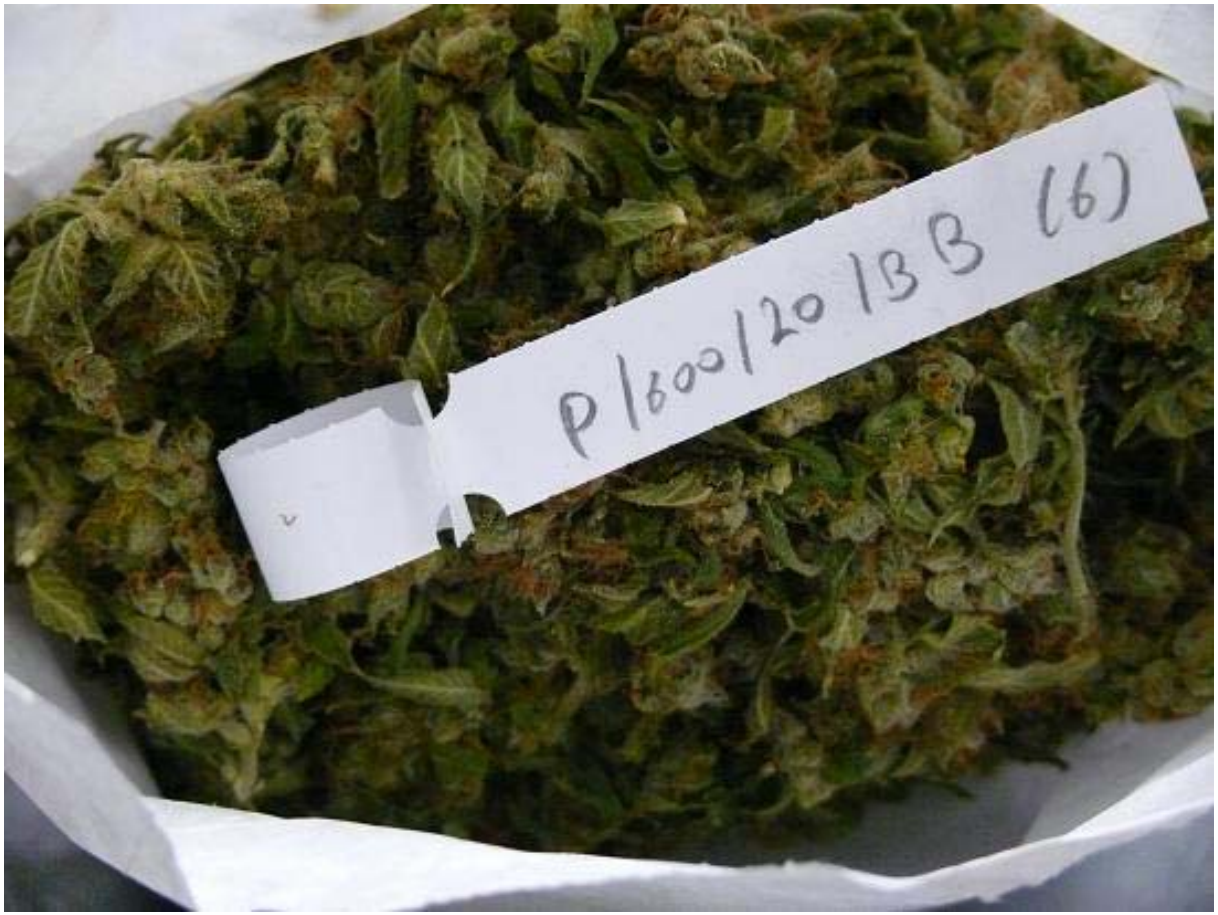


Fig. 3.12. *Harvested and dried female cannabis flower buds of a Big Bud plant, grown under 600 W lamps at a density of 20 plants per m², put in a paper bag prior to weighing (19 August 2010).*

3.2.2. Cycle 2: influence of plant density and reduced nutrition levels

3.2.2.1. Experimental design

The Belgian Federal Police commented on the experimental design of our first indoor cannabis growth cycle by stating that plant densities in Belgian indoor cannabis plantations rarely exceed 16 plants per m². Furthermore, some police officials and judiciary experts stated that fertilizer application as stipulated in the sophisticated growth schedule used during the first growth cycle (Table 3.1) might be performed inadequately, due to restricted access to fertilizers or out of mere ignorance. Such erratic fertilizer application might have a negative impact on yield. If so, the defense of indoor cannabis growers brought to trial, might plead that the amount of profits to be confiscated should be lower than the profits that are estimated based on the yield obtained under recommended fertilizer applications.

In order to address these comments, between 30 September and 30 December 2010, a second cannabis growth cycle was performed. It consisted of two full factorial experiments that were combined in a single split-plot design (Fig. 3.13):

1. experiment including all whole plots marked as FF (i.e. 'full fertilization') in Fig. 3.13. In this experiment, the influence of, and interaction between two factors on the yield of indoor cannabis was studied:

    a. three plant densities in whole-plots: 9, 12 and 16 plants per m² (as for the first grow cycle, we stress that the effect of the plant density factor in this experiment is confounded by pot size and shape (Lemaire & Morel, 2003) which differ between the considered densities (see § 3.2.2.2.) as applied in this experiment;
    b. 4 cannabis varieties (Super Skunk, White Widow, Northern Light #5 x Haze and Big Bud) (i.e. those used in the first cycle) in split-plots;

2. experiment with only 16 plants per m² (all whole plots on the left on Fig. 3.13) and in which the influence of and interaction between two factors on the yield of indoor cannabis was studied:
    a. two levels of fertilization in two whole-plots; i.c. a fertilization schedule equal to that of the first cycle (see § 3.2.1.3) (FF in Fig. 3.13); and a basic fertilization schedule with reduced levels of applied nutrients (BF in Fig. 3.13);
    b. 4 cannabis varieties (Super Skunk, White Widow, Northern Light #5 x Haze and Big Bud) (i.e. those used in the first cycle) in split-plots.

A split-plot instead of a completely randomized design was preferred, as was also the case in the first grow cycle (see § 3.2.1.1). Subplots with a given plant density would influence yield and development of plants in neighbouring subplots with other plant densities. As a result, just as was the case in the first growth cycle, split-plots with varieties were placed in the 3 whole-plots with different plant densities.

Fertilization through irrigation with the nutrient solution was performed at an approximately two-daily rate. Nutrient application was more convenient and spills between different fertilizer treatments were avoided by placing split-plots with different varieties in the 2 whole-plots (with densities of 16 per m²) with fertilizer treatments. In order to minimize mutual influence of whole plot treatments, whole plots in both experiments were separated by a 1 m wide corridor.

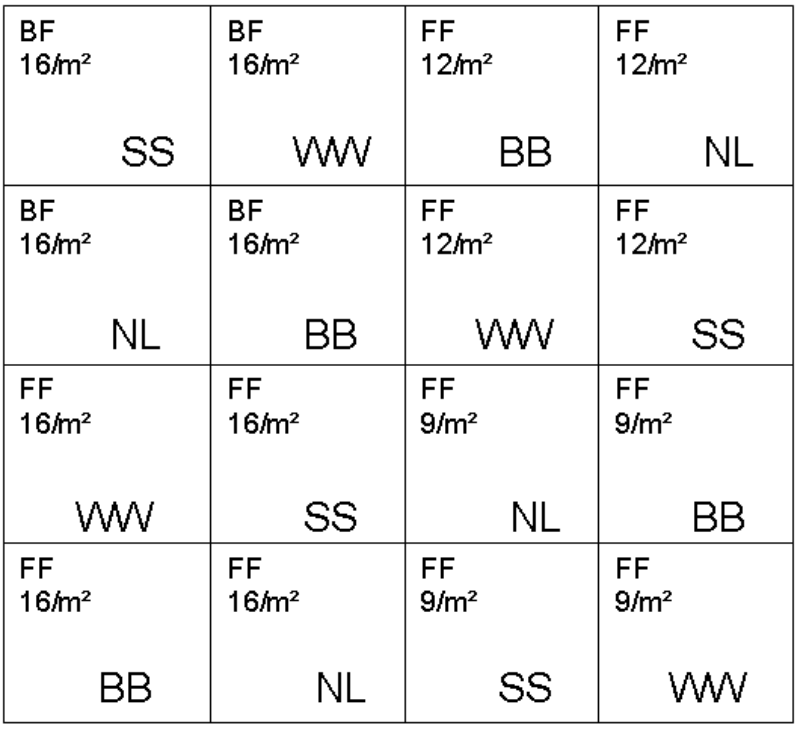


Fig. 3.13. *Experimental full factorial split-plot designs of the second cannabis cultivation cycle with plant densities (16 and 20 per m²) (first experiment) and fertilizer application (FF = Full Fertilization, BF = Basic Fertilization) (second experiment) in whole-plots; and varieties (SS = Super Skunk, WW = White Widow, NL = Northern Light #5 x Haze, BB = Big Bud) in split-plots.*

Table 3.2. *Fertilizer schedule applied in the second the cannabis cultivation cycle, based on the* Canna ® Terra *growth schedule* (*FF = Full Fertilization, BF = Basic Fertilization).* W*eeks are calendar weeks of 2010. – Product was not applied;*

In the last week of the BF treatment, no nutrients (only water) were applied.

Week	Licht u/dag	Terra Vega ml/10L	Terra Flores ml/10L	Rhizotonic ml/10L	Cannazym ml/10L	Cannaboost ml/10L	PK 13/14 ml/10L
FF							
39 - 42	18	20	-	40	-	-	-
43	12	40	-	15	25	-	-
44	12	-	60	5	25	30	-
45	12	-	55	5	25	30	15
46 - 51	12	-	60	5	25	30	-
52	12	-	-	-	25	30	-
BF							
39 - 42	18	15	-	-	-	-	-
43	12	35	-	-	-	-	-
44	12	-	55	-	-	-	-
45	12	-	55	-	-	-	-
46 - 51	12	-	55	-	-	-	-
52	12	-	-	-	-	-	-

3.2.2.2. Preparation

Cuttings for the second cycle were taken on 28 September 2010 from parent plants (obtained from randomly taken cuttings of plants in the first growth cycle) that were put in a separate room with 18 h of light (600 W high-pressure sodium lamps) per day and a nutrition of Terra Vega ® and Cannazym ® at a concentration of 40 ml and 25 ml per 10 L of irrigation water, respectively, in order to maintain them in a vegetative stage. Ten parent plants of each variety were thus raised. Terminal top and lateral branches were regularly pruned in order to remove apical dominance. This pruning stimulated lateral shoot formation. The latter then resulted in a considerable increase in terminal branches that could subsequently be used as tip cuttings. The latter were taken following the methods described in § 3.2.1.2, so that per variety a random mix of clones from the 10 parent plants was obtained. Plants in blocks with 16 and 12 plants per m² were planted in square pots (sides 0.25 m) of 11 L, whereas plants in blocks with 9 plants per m² were planted in round pots (diameter 0.33 m) of 27 L. Position of pots in each block of 1 m² of the plant density treatments is shown in Fig. 3.14.

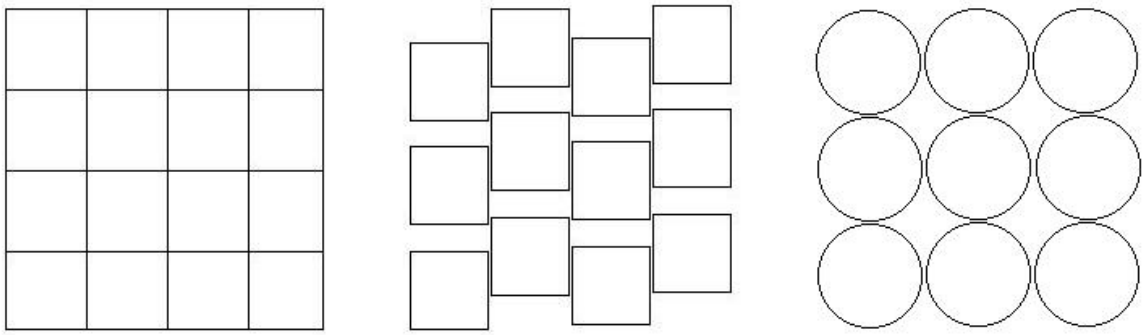


Fig. 3.14. *Position of pots per m² in blocks of 16 plants per m² (left) (11 L pots), 12 plants per m² (centre) (11 L pots) and 9 plants per m² (right) (27 L pots) in the experiment with different plant densities in the second cannabis growth cycle.*

3.2.2.3. Nutrition

In the experiment with different plant densities, as well as in the FF blocks of the experiment with full and reduced fertilizer applications (see Fig. 3.13), nutrients were applied following the same *Canna Terra* growth schedule as in the first cycle (see § 3.2.1.3). Instead of applying Growstar ® Gold Excelerator™ root stimulator, we used auxin-containing Rhizotonic™ of Canna ® was used (Table 3.2). In the reduced (basic) fertilizer treatment (BF), only basic NPK fertilizers Terra Vega™ (during the vegetative stage) and Terra Flores™ (during the flowering stage) were used (Table 3.2). Furthermore, both fertilizers in the BF treatment were applied in slightly lower concentrations than in the FF treatment (Table 3.2).

3.2.2.4. Environmental control

We decided to use only 600 W lamps in the second growth cycle, because it was shown that yield is significantly higher with 600 W lamps in comparison with 400 W lamps (see § 3.3.1.1 and Table 3.5), and growers will most likely use material that maximizes yield and thus profit. All other environmental circumstances were similar to those of the first growth cycle (see § 3.2.1.4). However, as a result of the decreasing outside temperatures (autumn and winter period) during the course of the cycle, warmth produced by the growth lamps was insufficient to keep the growth room temperature at an adequate level. Maximum and minimum temperatures follow the day and night rhythms as lights (that produce most of the warmth) were switched off between 6 pm and 6 am the following morning. After week 5 (4 November 2010, to be precise), maximum temperature dropped below the lower bound of the optimum range (20 °C) (Fig. 3.15). To remediate the latter problem, an electric oil heater (Sencys Oil-filled radiation, 2.5 kW) was installed in the growth room on 29 November 2010. Daily temperature extremes were measured with a minimum maximum thermometer, placed in the centre middle of the growth room, 1.5 m above the ground. By installing the oil heater, we were able to maintain maximum temperature again between 25 and 35 °C. However, the minimum temperature (reached during the night, when lamps were switched off), was always around or below 15 °C, even after the oil heater had been installed (Fig. 3.15). The latter will surely have had a negative impact on cannabis growth and development. This should

be taken into account when evaluating the results of the second growth cycle. Since plant development was slower as a result of low temperature, the second growth cycle lasted 14 weeks as compared to just 11 weeks for the first growth cycle.

3.2.2.5. Data collection

Data collection methods used in this second growth cycle were the same as those used during the first growth cycle (see § 3.2.1.5). Prior to analysis of variance, for both experiments, data of each split-plot was randomly divided in 4 parts to add a blocking factor (design contained no replicates). For each block thus obtained per split-plot, average yield per plant and average yield per m² were calculated. Analysis of variance was subsequently done using a nested model in the statistical software package R 3.0.1. Data exploration was done in SPSS 20. For multiple comparison of means between the four levels of the variety factor, the Least Significant Difference (LSD) was manually calculated using the mean square errors obtained in the split-plot analysis of variance (see above). In case in interaction effects between variety and other factors prevailed, multiple means comparison (with the LSD-method) between varieties was done also per whole plot (each with one of the densities under consideration), following Gomez & Gomez (1984).

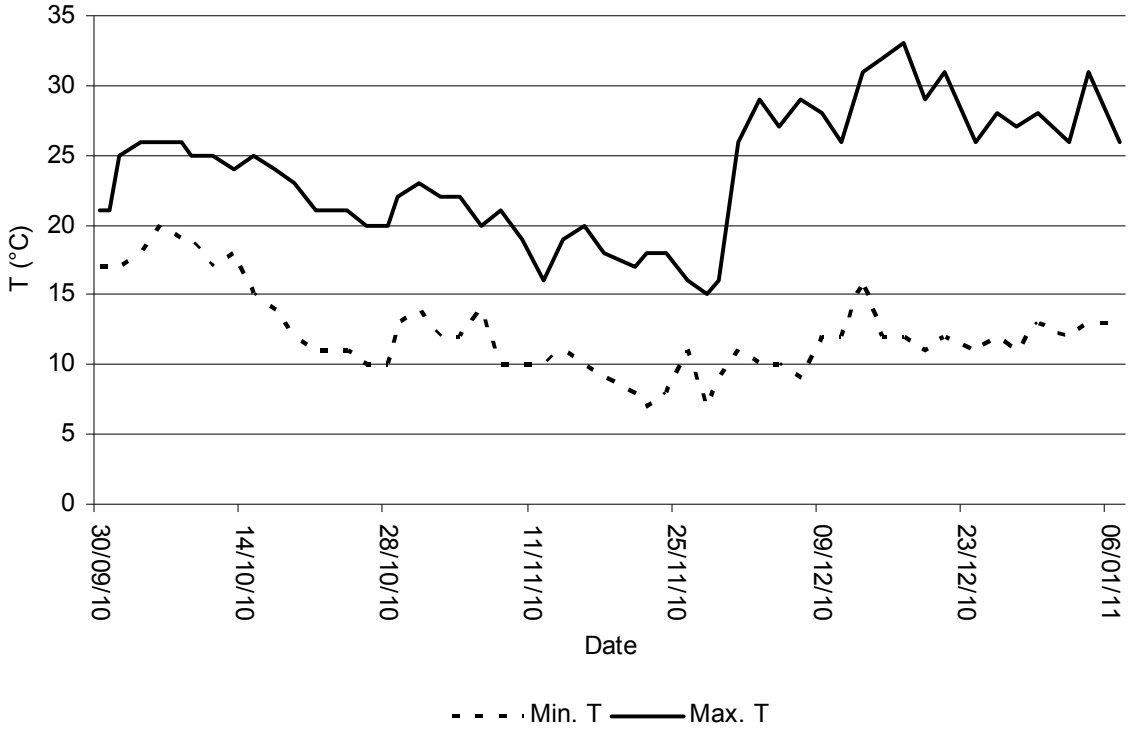


Fig. 3.15. *Daily measured minimum and maximum temperature in the growth room during the second growth cycle.*

3.3. Results

3.3.1. Cycle 1: influence of plant density, light intensity and variety

3.3.1.1. Yield

The growth cycle was completed in 11 weeks (or 837 GDD with T_{base} = 10 °C). At harvest, almost every plant bore one apical and in some cases several lateral female inflorescences. They consisted of buds with dark green calyxes containing brown or orange pistils, that formed a compact flowering mass, sometimes up to 8 cm thick and covering several internodes. Three plants were found to be stunted and without flower buds (two plants of the Big Bud variety under 400 W lamps, one in a block of 16 plants m^{-2}, the other in a block of 20 plants per m²; and one plant of the 'White Widow' variety grown under a 600 W lamp in a block of 16 plants per m²). The highest-yielding plant in the plantation was a Super Skunk plant grown under a 600 W lamp in a block of 16 plants per m² (48.3 g), whereas the lowest yield (0.4 g) was recorded for a White Widow plant in the same block.

Average yields per plant and per m² for each of the 16 factor combinations are shown in Table 3.3. Highest average yield per plant (28.0 g) was observed in the subplot of Big Bud plants, grown under a 600 W lamp with a density of 16 plants per m². Highest yield per m² (483.3 g per m²) was also found in a subplot of Big Bud plants, grown under a 600 W lamp, but with a density of 20 plants per m². Lowest average yield per plant (6.2 g) as well as lowest yield per m² (124.9 g) were found in the subplot with Northern Light #5 x Haze plants, grown under a 400 W lamp with a plant density of 20 plants per m².

Table 3.3. *Average yield per plant and per m², and THC, CBN and CBD concentration (%) of indoor cannabis for each of the 16 factor combinations (light intensity, plant density and variety) (NLX = Northern Light #5 x Haze) in the first growth cycle.*

				Yield (g per plant)		Yield (g per m²)		Concentrations (%)		
Light	Density	Variety	n	Mean	St. Dev.	Mean.	St. Dev.	THC	CBN	CBD
400 W	16 per m²	Big Bud	15	9.9 b	4.3	143 b	69	15.3	0.2	0.3
		NLX	16	11.6 bc	6.7	186 bc	108	10.9	0.2	0.2
		Super Skunk	16	18.6 a	8.0	339 a	165	14.3	0.3	0.3
		White Widow	16	8.9 c	6.6	143 c	105	9.7	0.2	0.2
	20 per m²	Big Bud	19	12.6 a	5.9	252 a	118	12.5	0.2	0.3
		NLX	20	6.2 b	4.2	125 b	84	13.3	0.2	0.2
		Super Skunk	20	11.3 a	6.2	225 a	124	12.8	0.2	0.3
		White Widow	20	13.0 a	6.2	260 a	124	11.7	0.2	0.3
600 W	16 per m²	Big Bud	16	28.0 a	8.3	448 a	133	15.9	0.2	0.3
		NLX	16	17.4 b	8.9	279 b	142	12.6	0.2	0.3
		Super Skunk	16	23.4 a	11.8	444 a	225	15.2	0.2	0.4
		White Widow	15	15.5 b	7.8	268 b	144	10.4	0.2	0.2
	20 per m²	Big Bud	20	21.1 a	9.3	483 a	232	14.8	0.2	0.4
		NLX	20	16.8 b	8.6	358 b	192	8.3	0.2	0.4
		Super Skunk	20	16.4 a	6.1	376 a	187	16.3	0.2	0.3
		White Widow	20	11.5 b	7.6	231 b	153	8.5	0.1	0.2

For each of the 4 light x density factor combinations, a separate ANOVA of both yield per plant and yield per m² was performed. Table shows only significant (LSD, p < 0.05) differences between varieties by means of lower-case letters (a, b and/or c).

Data for each factor combination were normally distributed (Kolmogorov-Smirnov test, $p > 0.1$). Table 3.4 shows the results of the analysis of variance. Considering only yield per plant, it was found that main effects of all three factors are significant ($p < 0.05$) with

- higher yields for plants grown under 600 W lamps in comparison with plants grown under 400 W lamps;
- higher yields for plants grown in subplots with a density of 16 plants per m² in comparison with yields of plants grown in subplots with a density of 20 plants per m²; and
- higher yields for Super Skunk and Big Bud varieties in comparison with Northern Light #5 x Haze and White Widow varieties (Table 3.5).

The same observations can be made when considering yield per m², except that there are no significant ($p < 0.05$) differences in yield (in g per m²) between blocks of 16 plants per m² and blocks of 20 plants per m². For yield expressed per plant as well as yield expressed per m², plant density and light intensity can be considered to be

additive factors ($p > 0.05$ for light * density interaction in Table 3.4). The variable variety is significantly interacting with both plant density and light intensity ($p < 0.05$ for light * variety and density * variety interactions in Table 3.4). Because of the latter interaction effect, multiple comparison of means between varieties was performed for each of the light x density split-plot (see § 3.2.1.5). Results (Table 3.3.) show that the observed distinction in yield between varieties Super Skunk and Big Bud on the one hand, and between varieties Northern Light #5 x Haze and White Widow on the other hand (Table 3.5) is predominantly caused by significant yield differences between these two groups in plots with 600 W lamps.

Table 3.4. *Results of the analysis of variance of the split-split-plot experiment on the effect of factors light, density and variety on the yield of indoor cannabis (first growth cycle). Significance levels of effect or interaction effect at the 0.05 level (*) or 0.01 level (**).*

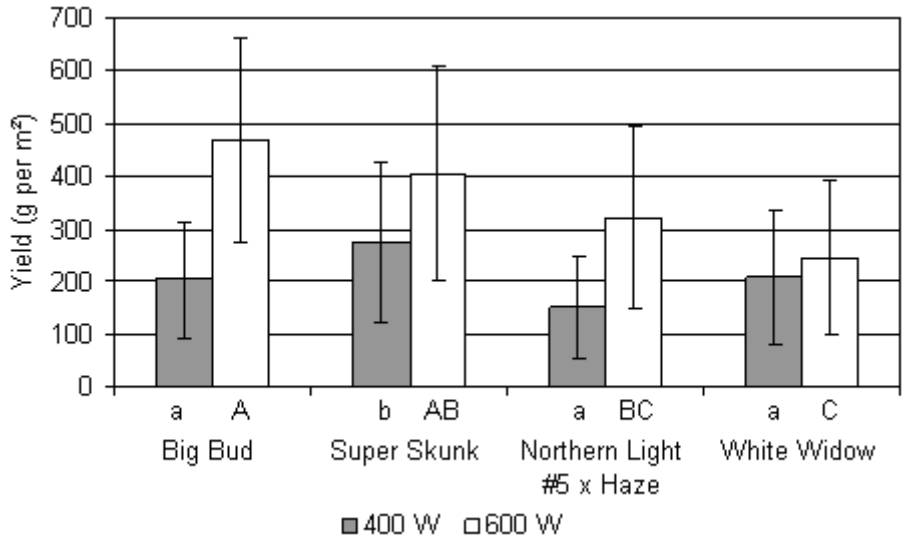
	Yield (g per plant)		Yield (g per m²)	
	F-value	p	F-value	p
Light	38.1	**0.001	48.6	**0.000
Density	7.5	**0.007	0.02	0.879
Variety	3.5	*0.027	4.6	**0.008
Light * Density	0.7	0.448	2.9	0.141
Light * Variety	2.2	*0.011	6.37	*0.024
Density * Variety	2.2	*0.011	1.2	*0.033
Light * Density * Variety	5.5	*0.034	2.7	*0.025

Fig. 3.16 shows that yield differences (in g per m²) between blocks with either 600 W lamps or 400 W lamps are relatively much higher for varieties Big Bud and Northern Light #5 x Haze than they are for varieties Super Skunk and White Widow. Within the blocks with 400 W lamps, yield (in g per m²) of plants of the Super Skunk variety is significantly ($p < 0.05$) higher than yield (in g per m²) of plants of the other varieties, whereas in 600 W lamp blocks, yield (in g per m²) of Super Skunk plants significantly ($p < 0.05$) equals yield of Big Bud plants whereas yield (in g per m²) of both varieties differs from yields of White Widow and Northern Light #5 x Haze plants.

Table 3.5. *Main effects of light intensity, plant density and variety on indoor cannabis yield and THC-concentration (first growth cycle).*

	Yield (g)						THC Concentration (%)			
	Per plant			Per m²						
	N	Mean		St. Dev.	Mean	St. Dev.	N	Mean		St. Dev.
400 W	142	11.7	a	7.5	211 a	131	8	12.6	a	1.8
600 W	143	20.1	b	11.1	362 b	198	8	12.8	a	3.3
16 plants per m²	126	17.6	a	11.3	282 a	181	8	13.0	a	2.5
20 plants per m²	159	14.5	b	9.3	290 a	187	8	12.3	a	2.8
Super Skunk	72	19.2	a	11.5	341 a	191	4	14.7	a	1.5
Big Bud	72	18.4	a	11.1	336 a	206	4	14.6	a	1.5
Northern Light #5 x Haze	70	13.3	b	9.0	240 b	165	4	11.3	b	2.2
White Widow	71	12.5	b	7.7	227 b	139	4	10.1	b	1.3

For each of the 3 factors, different lower-case letters (a, b) indicate significant differences ($p < 0.05$) between means. T-tests were used for comparing means between different light intensities and between different plant densities. Multiple comparison of mean yield and of mean THC concentrations between varieties was done using the LSD method ($p < 0.05$).



Error bars show standard deviation. Different lower-case letters (a and b) indicate significant ($p < 0.05$) differences (LSD) between varieties within the 400 W series, different capitals (A, B and C) show significant ($p < 0.05$) differences (LSD) between varieties within the 600 W series.

Fig. 3.16. *Mean yield (g per m²) of four different cannabis varieties grown indoors under 400 W and 600 W lamps (first cannabis growth cycle).*

3.3.1.2. Cannabinoid concentrations

Highest THC concentration (16.3 %) was found for a sample of Super Skunk plants grown at a density of 20 plants per m² under 600 W lamps. Lowest THC concentration (8.3 %) was detected with a sample of Northern Light #5 x Haze plants grown under the same conditions. Mean values of CBN and CBD concentrations were 0.2 % and 0.3 %, respectively, with very little variation (standard deviations of 0.04 and 0.07, respectively) (Table 3.3). Since only 16 THC measurements were performed, analysis of variance was not possible and consequently, interaction effects of factors on THC concentrations could not be examined.

Considering main effects of three growth factors on THC concentrations, only the variety factor proved to be significant ($p < 0.05$, LSD). Highest average THC concentrations were found with the Super Skunk and Big Bud variety (14.7 % and 14.6 %, respectively), which also had the highest average yield values (see previous section) (Table 3.5). Factor effects on CBN and CBD content were not statistically analysed given the little variation in both concentrations.

3.3.2. Cycle 2: influence of plant density and reduced nutrition levels

3.3.2.1. Experiment with lower plant densities

Due to the low temperature (see § 3.2.2.4 and Fig. 3.15), it took 14 weeks (or 808 GDD with T_{base} = 10 °C) to complete the second cannabis growth cycle. For unclear reasons, the growth cycle was characterized by much more competition between plants than during the first growth cycle. At harvest, a large number of plants (35 %) had withered or had produced no flower buds because other plants were able to grow faster so that they captured most of the light energy before it could reach the lower plants. Plant loss was most considerable in blocks with 12 plants per m² (44 %) and in blocks with the Big Bud variety (54 %). Yield figures are reported in Table 3.6. N values show the number of plants in each block that produced a significant (i.e. > 5 g dry weight) amount of cannabis flower buds. In order to calculate meaningful yield data per m², the yield per plant was multiplied by the effective number of plants in the respective blocks (N values in Table 3.6). Indeed, if a number of plants perishes during the growth cycle, the remaining plants will make relatively more use of the available light, and will consequently have a higher yield in comparison with blocks where no plants were lost.

Table 3.6. *Mean yield and standard deviations of the second cannabis growth cycle for 12 factor combinations (3 plant densities x 4 varieties).*

			Yield (g per plant)		Yield (g per m^2)	
Density	Variety	N	Mean	St. Dev.	Mean	St. Dev.
16 plants per m²	Super Skunk	16	61.6 a	25.7	985 a	411
	Big Bud	9	45.7 a	21.8	411 b	196
	White Widow	8	33.4 a	15.9	267 b	127
	Northern Light #5 x Haze	10	28.0 a	13.5	280 b	135
12 plants per m²	Super Skunk	10	75.8 ab	33.6	758 a	336
	Big Bud	4	114.6 a	83.4	458 ab	334
	White Widow	9	55.1 b	17.4	505 b	156
	Northern Light #5 x Haze	4	34.7 b	10.3	139 b	41
9 plants per m²	Super Skunk	9	95.6 a	49.9	860 a	449
	Big Bud	4	53.6 bc	24.4	214 b	98
	White Widow	6	79.8 bc	37.7	479 b	226
	Northern Light #5 x Haze	7	64.1 c	19.5	448 b	137

For each of the 3 density factors, a separate ANOVA of both yield per plant and yield per m² was performed. Table shows only significant (LSD, $p < 0.05$) differences between varieties by means of lower-case letters (a, b and/or c).

Highest mean yield per plant was recorded in the block with 12 Big Bud plants per m². However, highest mean yield per m² was recorded in the block with 9 Super Skunk plants per m². Comparison of mean yield in the block with 16 plants per m² with mean yield of the block with 16 plants per m² and 600 W growth lamps of the first cycle (Table 3.3.) shows that the mean yield per plant was higher in the second than in the first growth cycle (increases of 10.6 g per plant for Northern Light #5 x Haze plants, 17.9 g per plant for White Widow, 17.7 g per plant for Big Bud, and 38.2 g per plant for Super Skunk variety). However, yield per m² was more or less equal to that of the first growth cycle, except for mean yield per m² of Super Skunk blocks where the mean yield per m² increased with 541 g per m².

Data for each factor combination were normally distributed (Kolmogorov-Smirnov test, $p > 0.05$). Just as with the first growth cycle, significant ($p < 0.005$) differences occur in mean yield per plant between different plant densities and different varieties. Both factors (density and variety) show significant interaction effects (Table 3.7). Because of the latter interaction effect, multiple comparison of means between varieties was performed for each of the density whole plots (see § 3.2.2.5). Results of multiple comparisons per density whole plot (Table 3.6.) as well as for the complete experiment (Table 3.8) indicate that the Super Skunk variety has a significantly ($p < 0.05$) higher yield in comparison with other varieties, particularly when yield is expressed in g per m². Mean yield per m² was significantly different between varieties, but not between different plant densities.

Table 3.7. *Results of the analysis of variance of the split-plot experiment on the effect of factors density and variety on the yield of indoor cannabis (second growth cycle). Significance levels of effect or interaction effect at the 0.05 level (*) or 0.001 level (**).*

	Yield (g per plant)		Yield (g per m^2)	
	F-value	p	F-value	p
Density	2.63	*0.015	1.0	0.412
Variety	1.8	*0.017	13.9	**0.000
Density * Variety	2.22	*0.040	3.51	*0.011

Mean yield per plant was significantly lower ($p < 0.05$) for the plants in blocks with 16 plants per m² than for blocks with lower plant densities (Table 3.8). Just as with the first growth cycle, also in the second cycle, there were no significant

differences in the per m² yield between blocks of the three plant densities under consideration. The lower bound of the one-sided 95 % confidence interval for the yield per m² for the aggregate of all plants in this experiment was 462 g.

Table 3.8. *Main effects of plant density and variety on the yield of indoor cannabis in the experiment with 3 plant densities and 4 varieties in the second cannabis growth cycle.*

		Yield (g per plant)				Yield (g per m²)			
	N	Mean		St. Dev.	Lower Bound one-sided 95 % conf. int.	Mean		St. Dev.	Lower Bound one-sided 95 % conf. int.
9 plants per m²	26	77.0	a	38.8	64.0	562	a	370	438
12 plants per m²	27	68.9	a	43.3	54.7	537	a	323	432
16 plants per m²	43	45.2	b	24.6	38.9	567	a	427	458
Super Skunk	44	72.0	a	35.0	63.2	822	a	393	723
Big Bud	26	58.9	ab	44.7	43.9	401	b	249	317
White Widow	30	48.2	ab	28.1	39.5	364	b	196	303
Northern Light #5 x Haze	26	40.3	b	20.8	33.4	285	b	159	232

Mean comparison was done at the 0.05 significance level (Least Significant Difference); comparison of mean yield figures between different varieties was done using the Dunnett T3 method due to unequal variances.

3.3.2.2. Influence of reduced plant nutrition

Reducing the fertilizer application to a basic level does not have a negative effect on cannabis yield per plant. On the contrary, per plant yield of varieties Super Skunk, Big Bud and Northern Light #5 x Haze was even higher in blocks with a basic fertilization than for blocks with the full fertilization (Table 3.9).

Table 3.9. *Mean yield and standard deviations for 8 factor combinations (2 fertilizer treatments and 4 varieties) of the second cannabis growth cycle.*

			Yield (g per plant)		Yield (g per m^2)	
Fertilization	Variety	N	Mean	St. Dev.	Mean	St. Dev.
Full	Super Skunk	16	61.9	25.7	985	411
(FF in Fig. 3.13)	Big Bud	9	45.7	21.8	411	196
	White Widow	8	33.4	15.9	267	127
	Northern Light #5 x Haze	10	28.0	13.5	280	135
Basic	Super Skunk	9	62.9	25.1	566	226
(BF in Fig. 3.13)	Big Bud	9	49.7	33.0	447	297
	White Widow	7	28.0	8.9	196	62
	Northern Light #5 x Haze	5	36.2	15.4	181	77

Data for each factor combination were normally distributed (Kolmogorov-Smirnov test, $p > 0.05$). Analysis of variance (Table 3.10) shows that indeed no significant ($p < 0.05$) differences prevail in per plant yield between both fertilizer treatments (main effect). However, the main effect of reducing fertilizer application is significant ($p < 0.05$) when yield is expressed in g per m². Also, there is a significant ($p < 0.05$) interaction effect between factors fertilization and variety: in contrast with other varieties, with Big Bud, mean per m² yield increases when fertilization is reduced to a basic level (Table 3.9).

Table 3.10. *Results of the analysis of variance of the split-plot experiment on the effect of factors fertilizer treatment and variety on the yield of indoor cannabis (second growth cycle). Significance levels of effect or interaction effect at the 0.01 (*) or 0.001 level (**).*

	Yield (g per plant)		Yield (g per m^2)	
	F-value	p	F-value	p
Fertilization	1.8	0.376	5.4	0.045
Variety	5.7	*0.006	10.9	**0.000
Fertilization * Variety	0.2	0.912	0.9	0.051

If only the main effect of reducing fertilization to a basic level is considered, mean per m² yield and the lower bound of the one-sided 95 % confidence interval decreases with 188 g per m² and 158 g per m², respectively (Table 3.11). However, the latter findings have little practical significance because of the many plants that were lost during the second growth cycle (33 % in the block with full fertilization and 53 % in blocks with a basic fertilization).

Table 3.11. *Main effect of the fertilizer treatment on the mean yield per m² and on the lower bound of the one-sided 95 % confidence interval.*

Fertilization	Yield (g per m²)	Lower bound of the one-sided 95 % confidence interval (g)
Full (FF)	567	458
Basic (BF)	380	300
Difference	188	158

3.4. Discussion and conclusions

Indoor cannabis yield depends on a number of factors, of which at least three proved to have significant effects in our study: light intensity above the canopy, plant density and variety. Cannabis grown under 600 W lamps has a higher yield than cannabis under 400 W lamps. In the first growth cycle, average yield per plant was higher with a plant density of 16 plants per m² when compared to average yield of plants grown at a density of 20 plants per m². However, there was no significant difference ($p < 0.05$) between yields from both plant densities when yield was expressed per m². This conclusion also holds for the second growth cycle in which lower plant densities (9, 12 and 16 plants per m²) were applied.

The effect of factor plant density studied in both growth cycles, is confounded by both pot shape (Lemaire & Morel, 2003) and volume. Plants that are close to other plants compete with the latter plants for light, because of overlapping branches and leaves. Increasing the plant density in a cultivation experiment will consequently reduce the average per plant yield, due to reduced photosynthetic assimilation (see also Box 1 § 2.3.2). Evaluation of the effect of different plant densities on per plant yield would require *ceteris paribus* of all other growth factors. However, in our experiments, pot volume and shape were additional factors that in some cases differed between different 'plant densities'. It is clear that more nutrients were available to plants grown in 27 L pots (for plants grown at a density of 9 per m²) than in 11 L pots used in plots with plant densities of 12 and 16 per m²; or than in 5 L pots used in plots with plant densities of 20 per m². Also, roots might develop differently in square pots as compared to circular pots. In the latter, roots will tend to spiral around the pot walls resulting in a different root architecture as compared to roots developing in square pots. However, root spiraling specifically occurs in older seedlings (e.g. in propagation of forestry plants with tap roots) (Tsakaldimi *et al*., 2005). Plants in our experiments were harvested after 11 to 14 weeks, and root spiraling was not observed upon harvest. Moreover, total root biomass is mostly determined by pot volume rather than by pot shape (Lemaire & Morel, 2003). Since root spiraling was not observed, differences in pot shape will not significantly confound the effect of the plant density factor on cannabis yield. In illicit indoor cannabis plantations, growers

will usually make optimally use of the available ground surface area. As a result, plants at higher densities will be placed in smaller pots, thus reducing the amount of soil for root development and nutrient uptake in comparison with plants at a lower density. Plants at higher densities will consequently not only compete for light but also for soil nutrients. However, in order to evaluate the real plant density effect, subsequent growth experiments with different plant densities should use pots with equal volume and shape.

All these findings taken together indicate that light intensity is the limiting factor in indoor cannabis production. Plants at lower densities intercept more light, have a higher photosynthesis rate and consequently a higher production (Van Der Werf, 1997). In illicit cannabis growth rooms where floor space is often scarce, loss of yield per plant at higher plant densities is compensated by a higher number of plants per m². A study on the effect of growth and development of a fibre hemp variety (Kompolti Hibrid TC) at four plant densities (10, 30, 90 and 270 plants per m²) in the Netherlands (open field), revealed that flowering was delayed with increasing plant density (van Der Werf, 1997). However, this effect was not observed in our indoor cannabis growth setting, where flowering dates were more or less equal for all plant densities considered.

According to the production model of Toonen *et al*. (2006), optimum plant density is 32 plants per m² which would yield 608 g per m², or 19 g per plant. However, the latter model does not include differences that might arise across cannabis varieties. In our study, we found that factor variety interacts with factor plant density for both per plant yield and per m² yield.

Based on interviews with 15 indoor, soil-based cannabis growers in Quebec province, Canada, Bouchard (2008) reports yield figures of 284 g per lamp (median lamp power was 600 W), which is below the yield figures for 600 W lamps found in both growth cycles of our experiments. However, Bouchard (2008) does not mention lamp density. Since in Canada use of non-metric units is still widespread, it is not certain that one lamp also covers 1 m², as is the case in most Belgian indoor cannabis plantations. As a result, the low yield data reported by Bouchard (2008) might be explained by application of light densities < 1 per m².

Bedrocan BV company obtains an average yield of 315 g per m² for the sativa-type Bedrocan® variety and an average yield of 251 g per m² for the indica-type Bedica® variety (hydroponics system with a plant density of 2.33 plants per m² and a overhead light intensity of 423 W per m²), which concurs with mean yields found in plots with 400 W lamps in our study (information obtained from Bedrocan BV Nederland, official grower of cannabis for medicinal purposes under the authority of the Ministry of Health, Welfare and Sport, Bureau of Medicinal Cannabis, The Hague, The Netherlands).

Recently, Knight *et al*. (2010) also produced cannabis in three growth cycles of six plants each, using the so-called 'screen of green' (ScrOG) method in which branches are supported by a wire mesh, allowing the formation of a canopy that is distributed evenly along the horizontal plane. As a result, ScrOG cultivation systems capture light more efficiently in comparison with other indoor cannabis cultivation systems. Varieties used are unknown, but genetic fingerprinting, performed by Knight *et al*. (2010), and subsequent principal component analysis revealed 3 distinct groups. Yield figures obtained in this study are considerably higher than in ours: between 350 g and 1340 g per plant. Unfortunately, the work of Knight *et al*. (2010) is of little value as a benchmark to the present study due to the limited number of plants, the lack of information on the varieties used and particularly because of the non-disclosure of cultivation methods (light intensity, plant density, fertilizers used, etc.). The latter information is restricted to the New Zealand law-enforcement community in order to protect police operational concerns (Knight *et al*., 2010).

The most useful benchmark study was performed by Potter & Duncombe (2011) who used contrasting 250 W and 1000 W Philips SON-T high pressure sodium lamps to provide light intensities of 270, 400 and 600 W per m². The latter treatment was imposed to 7 cannabis varieties (Early Pearl, Hindu Kush, Super Skunk, White Widow, Wappa, White Berry and G1). Five plants per variety were cultivated at a density of 10 plants per m². The main effect of light intensity on average dried flower bud yield per m² (422, 497 and 544 g per m² under intensities of 270, 400 and 600 W per m², respectively) confirms our findings that per m² yield increases with increasing light intensities. Two of the varieties used by Potter & Duncombe (2011) (Super Skunk and White Widow) were also used in our study. In both growth cycles, we

found significantly lower mean yield for White Widow plants in comparison with Super Skunk plants (Tables 3.8 and 3.5). If only the data of the blocks with 9 plants per m² (most closely approaching the plant density used in the study of Potter & Duncombe (2011)) of our second growth cycle are considered (Table 3.6.), mean yield of Super Skunk plants was 860 g per m² whereas mean yield of White Widow plants was 479 g per m². Potter & Duncombe (2011) report mean yields of Super Skunk plants of 540 g per m² as compared to a mean yield of 480 g per m² for White Widow plants. However, the latter authors did not statistically test for differences in yield between different varieties.

Our study shows that light intensity and plant density are additive factors, whereas factor variety is interacting with both light intensity and plant density. In our first growth cycle, apart from the Big Bud variety produced at a density of 16 plants per m² and under a light intensity of 600 W per m², all blocks had average yields lower than 28.1 g per plant, the reference figure that was proposed by Toonen *et al*. (2006). In our second growth cycle, however, average per plant yield figures for all factor combinations were well-above 28.1 g per plant. As a result of increased experience with cannabis growing in the second growth cycle, in blocks with 16 plants per m², average yield per plant was 45.2 g, whereas in the first growth cycle average yield per plant in blocks with 16 plants per m² (600 W blocks only) was just 21.2 g.

When the fertilizer application was lowered to a basic level in blocks with 16 plants per m², average cannabis yield decreased with 188 g per m² in comparison with blocks that had received full fertilization treatment (i.e. a reduction by 33 % of average yield per m²) (Table 3.11). However, this finding must be addressed with some reserves. Temperature in the growth room was suboptimal during the whole second growth cycle. As a result, on a total of 128 plants used in the experiment with fertilization treatments, 55 (43 %) withered during the cultivation period, causing competitive advantages of certain plants that had more space in comparison with others.

Growth cycle duration was 11 weeks in the first growth cycle, but amounted to 14 weeks in the second growth cycle due to heating problems which resulted in sub-

optimum temperature during a considerable part of the latter growth cycle. However, growing degree days (T_{base} = 10 °C) were 837 and 808 for the first, respectively second growth cycle. The latter finding indicates that growth cycle duration is better expressed in GDD than in a fixed number of weeks. The results currently do not allow defining an optimal GDD requirement for indoor cannabis cultivation.

THC concentrations (8.3 % - 16.3 %) reported in our study are slightly below the range found by Rigter & Niesinck (2010) in *nederwiet*, but well-above THC concentrations of imported cannabis (varieties not specified) that may range between 5 % and 10 %. In the United Kingdom, analysis of cannabinoid concentrations of 247 samples taken from the same confiscated indoor grown cannabis plantations in 2004/5, revealed high variations in level of THC: minimum concentration was 1.15 %, whereas maximum concentration was 23.17 %; the median sample had a THC content of 23.17 % (Potter *et al*., 2008). The latter study, however, contained samples that had been stored by police at room temperature for more than a year. This will inevitably have affected cannabinoid contents. More precisely, some THC will have been degraded (oxidized) into CBN. In a similar research in Japan in 2010, only fresh samples, i.e. those with a CBN/THC ratio ≤ 0.1 (335 samples), were used to study cannabis potency. THC levels found were between 0.2 and 22.6 % with an average THC concentration of 11.2 % (Tsumura *et al*., 2012). These results show that high-potent cannabis varieties, equal or similar to those that are widespread in Europe, also prevail in Japan.

Considering only the main effect of cannabis varieties, it was found that varieties with the highest yield also have the highest THC concentration. It was shown that differences in THC concentrations are predominantly linked with genotypic variation, rather than with cultivation factors such as those considered in our study (plant density and light intensity). Pate (1999) claims temperature may play an important role in cannabinoid synthesis in *Cannabis* spp. According to Sikora *et al*. (2011), THC synthesis in industrial hemp is positively correlated with growing degree days (GDD) and air humidity, whereas it is negatively correlated with precipitation. However, in our experimental growth cycles, we did not test different temperature regimes nor different irrigation frequencies.

Just as in our study, Potter and Duncombe (2011) did not find any significant differences in mean THC concentrations between different light intensities. They did observe, however, considerable variability in THC concentrations of flower buds between the 7 considered varieties (not statistically tested). In our study, we found THC concentrations in Super Skunk plants ranging 12.8 - 16.3 %, whereas average THC concentration in the 15 Super Skunk plants cultivated in the study of Potter and Duncombe (2011) was 19.1 %. Furthermore, in our study, THC concentrations of White Widow plants varied between 8.5 and 11.7 %, whereas in the study of Potter and Duncombe (2011), the same variety fetched much higher concentrations of (17.6 % on average). The latter indicates that the White Widow variety is unstable in its phenotypic expression of THC production, or that breeders and seed traders (deliberately) mislabel cannabis varieties.

In jurisdiction in the Netherlands, until 2008 yield figures were based on an investigation by Huizer & Poortman-van der Meer (1995) who claimed that a confident estimation of indoor cannabis yield was 22 g per plant. However, this research was based on extrapolations and projections from immature, confiscated plants entailing inaccurate yield estimations. Since 2008, Dutch jurisdiction is based on the research by Toonen *et al*. (2006) who used data obtained from 77 confiscated cannabis plantations in the Netherlands. The latter authors performed a linear regression with cannabis yield as the dependent variable, and with three explanatory variables: plant density, light intensity and plant developmental stage (ranging 1 (the onset of flowering) to 10 (the harvest stage with fully developed flowers)). The one-sided 95 % confidence interval for the cannabis yield, predicted by linear regression using the values of the median grow room in their study (plant density: 15 per m²; light intensity; 510 W per m²) and a plant developmental stage of 10 (28.1 g), was proposed as a reliable estimate of the yield of indoor cannabis in the Netherlands.

Our study shows that yield of illicit cannabis plantations can not be straightforwardly estimated as a number of grams per plant. Overall production depends on growth factors such as plant density, light intensity and variety used, all of which interact in their effect on cannabis yield.

However, we found inconsistencies in yield figures between the two indoor cannabis growth cycles and faced environmental problems that occurred during the second growth cycle. The latter problems were caused by lack of experience with cannabis growing, resulting in inadequate timing (4 weeks for the vegetative stage probably directed too much energy to the development of vegetative plant parts at the cost of flower production), inadequate plant support (bamboo sticks were installed after many branches had already snapped) and night temperatures that might have been below optimum levels (minimum temperature was not recorded during the first growth cycle). The latter observations urge for an indoor cannabis growth experiment in which growth factors are optimized in a way that would be done also by experienced illicit growers. The latter would allow for more accurate estimates of the real yield of cannabis produced indoors. Further cannabis growth cycles will also have to include other - possibly higher-yielding varieties, or varieties that are frequently confiscated by police (but of which the variety name is usually unknown).

To conclude with, in following growth experiments, the flaws of the experimental design reported in this chapter need to be addressed. Using a split-split-plot design complicates statistical analysis and reduces the significance of statistical differences and interaction effects between factor levels in comparison with a completely randomized full factorial design. Furthermore, since the experimental blocks in the two growth cycles reported in this chapter contained no replicates, an artificial blocking factor had to be included in order to perform analysis of variance. The thus created virtual blocks do not take real environmental variation between replicated blocks into consideration, as would be the case if replicates were spatially separated. Given the amount of factors studied in the reported growth cycles, presence of hard-to-change factors (density and light) and for practical reasons (limited size of the growth room), however, this was not possible in the first two growth experiments reported in the present chapter.

CHAPTER 4 A practical estimate of yield of Belgian indoor cannabis plantations

Adapted from:

Vanhove, W., Surmont, T., Van Damme, P. & De Ruyver, B. (2012). Yield and turnover of illicit indoor cannabis (*Cannabis* spp.) plantations in Belgium. Forensic Science International, 220(1-3), 265-270.

4.1. Introduction

Today, the Belgian judiciary uses a crop yield estimation made by the University of Wageningen, The Netherlands (Toonen *et al*., 2006) and set at 28.1 g of dry female flower buds per plant (lower bound of the one-sided 95 % confidence interval). Observations made by Belgian police at confiscation of indoor cannabis plantations during the past few years nevertheless suggest that illicit growers nowadays achieve plant yields that are much higher than 28.1 g per plant. A reliable estimate of the currently obtained yield in Belgian indoor cannabis plantations is needed in order to correctly calculate profits to be confiscated by the judiciary (see also § 1.1).

In chapter 3, we showed that variety is the main yield-determining factor in indoor cannabis production. We used state-of-the-art growing techniques (i.e. high-power assimilation lamps, atmospheric control through turbines with carbon filters and a standardized fertilization schedule) to reveal most relevant yield- determining factors. However, so far, we failed to obtain yield figures that concur with recent police observations.

In this chapter, we report results of a third cannabis growth cycle in which the problems that occurred during the first two cycles, were thoroughly addressed. The objective of this chapter is to optimize indoor cannabis cultivation as described in Chapter 3, with the aim to propose a realistic and scientifically sound yield figure of current indoor cannabis cultivation.

4.2. Material and methods

Growth experiments built on the research methodology developed in our first two growth cycles. Experiments (14 February 2011 – 29 April 2011) were performed in the same growth room under similar environmental conditions as described in § 3.2. In this section, material and methods will be presented in detail when and where they differ from those described in § 3.2.

4.2.1. Experimental design

Since it was shown that yield under overhead lights of 600 W is significantly higher than yield under 400 W lamps (Table 3.5, § 3.3.1.1), and assuming that most growers will use material that generates the highest yield and thus profit, growth experiments were performed only using 600 W lamps. Federal Police further commented on the first two growth cycles (chapter 3) by stating that plant densities as high as 20 plants per m² are rarely encountered. The growth cycle reported in this chapter therefore used and compared more realistic plant densities of 12 and 16 plants per m². Moreover, we have avoided confounding of the effect of the plant density factor by additional factors 'pot shape' and 'pot volume' that occurred in the experiments of the first two growth cycles (chapter 3) by using pots with equal volume (11 L) and shape (square) in both plant density blocks. As such, we are now able to evaluate the real plant density effect, *ceteris paribus*. Toonen *et al*. (2006) studied 77 confiscated indoor cannabis plantations in the Netherlands and showed that 30 (39 %) had plant densities in the range of 9 to 16 plants per m², whereas 20 plantations (26 %) had plant densities in the range of 17 to 24 plants per m² and only 12 (16 %) plantations had plant densities in the range of 25 – 32 plants per m². The latter figures confirm that densities of 12 and 16 plants per m², used in the present study, cover a realistic plant density range.

The experiment consisted of a full factorial split-plot design with two replicates of two whole-plots, each consisting of a different plant density (12 and 16 plants per m²). Whole plots were separated by a 1 m wide corridor to minimize mutual influence

of whole plot treatments. Each of the whole-plots was divided in 4 split-plots, each with a different cannabis variety. Replicates were placed in adjacent blocks with whole-plots positioned crosswise and with varieties placed so that the factor variety in the complete design formed a Latin square (Fig. 4.1).

16/m² BB	16/m² SK	12/m² SH	12/m² XX
16/m² XX	16/m² SH	12/m² SK	12/m² BB
12/m² SK	12/m² BB	16/m² XX	16/m² SH
12/m² SH	12/m² XX	16/m² BB	16/m² SK

Fig. 4.1. *Experimental full factorial split-plot design of the third cannabis cultivation cycle with plant densities (12 and 16 per m²) (first experiment) in whole-plots; with in each whole-plot varieties (BB = Big Bud, SK = Skunk #1, SH = Silver Haze #9, X = unknown variety) in split-plots; and with two replicates.*

4.2.2. Varieties

In order to cover more of the variability of frequently used cannabis varieties, we added two new varieties (Skunk #1 and Silver Haze #9) to the third growth cycle, whereas Super Skunk, Northern Light #5 x Haze and White Widow, used in the first two cycles (see chapter 3), were no longer considered. The growth experiment thus used four cannabis varieties; i.e. Skunk #1, Silver Haze #9, Big Bud and an unknown variety X. Skunk #1 and Silver Haze #9 were propagated by cuttings from seedlings that were produced from feminized seeds which were purchased on July 8, 2010 from the Sensi Seed Bank (Amsterdam, The Netherlands). Propagation procedure was equal to the protocol used in the first two growth cycles (§ 3.2.1.2). Cuttings were taken so that a random mix of clones from the ten parent plants per variety was obtained. Variety Big Bud was propagated by cuttings from parent plants that were retained after the second growth cycle had been completed. Big Bud was retained as a variety in the present study, because in the first growth cycle, this variety gave the highest mean yield (335.78 ± 205.63 g per m²) (Table 3.5, § 3.3.1.1). In the second growth cycle, however, highest yield was obtained for the Super Skunk variety (Table 3.8, § 3.3.2.1). Since the latter finding is based on an experiment with inadequate environmental control (see § 3.2.2.4), we decided not to take the second growth cycle as a reference for variety selection. Including variety Big Bud in the present study allows for benchmarking yield figures with results obtained in our first two growth cycles (§ 3.3). The unknown variety X was obtained from 10 uniform cuttings (rooted in rock wool cutting blocks, plant height between 20 and 30 cm) that police confiscated early July 2010 at a typical Belgian indoor cannabis plantation. It will allow to benchmark crop yield figures of the other three varieties obtained from Dutch growshops. Significant differences between the yield of variety X and that of the other varieties would indicate that illicit growers might use seedlings from breeders, others than those who supply the Dutch growshops. Cuttings from variety X were cultivated to mother plants that were subsequently propagated following methods presented in § 3.2.1.2.

4.2.3. Cultivation

The growth cycle started on 14 February 2011 with potting of rooted cuttings and finished with harvest on 29 April 2011 (week 11). Rooted cuttings were placed in square pots of 11 L (sides of 0.25 m; height: 0.21 m) and positioned in 4 rows of 4 pots (yielding plots with 16 plants per m²) or in 4 perpendicular rows of 3 pots (yielding plots with 12 plants per m²), similar to pot positioning of these plant densities in the second growth cycle (see Fig. 3.14., §3.2.2.2). Philips ® Master SON-T PIA Plus E40 high pressure lamps of 600 W were positioned above the centre of each block of 1 m². Pots were filled with peat soil (pH 6.4, OM: 20%) that was mixed with 5% perlite, following Green (2001).

Nutrition was applied according to the Canna Terra growth schedule (http://www.onlinegrowsupplies.com/CANNA_Terra_kweekschema.pdf; last visit: 02 December 2013) (Table 4.1). For details on fertilizers and additives used, we refer to § 3.2.1.2. Growth cycle consisted of a vegetative stage of 2 weeks (18 hours of light per day) and a flowering stage of 9 weeks (with 12 hours of light per day). Environmental control measures were similar to those described in § 3.2.1.4. However, some adjustments were made to optimize temperature regime in the growth room.

Green (2001) and Adams (2007) claim that the optimum temperature in a cannabis growth room ranges 20 to 25 °C. Since growth experiments were performed in winter when outdoor temperatures frequently dropped below zero, lamps alone could not sufficiently heat the growth room. To deal with this problem, an electric heater (Eurom EK3301, 3.3 kW) was placed in the growth room under a Honeywell NV-1800E ventilator (flow rate: 6100 m³ per h). The latter guarantees even air circulation so that temperatures are equal throughout the growth room. Further, an additional thermostat was connected to the Torinsifan RIC which controls the turbines that evacuate hot air (resulting from lamps) and cannabis odour through carbon filters. Since removal of the latter is crucial in order to avoid exposure of illicit indoor cannabis plantations, the RIC always maintains a basic flow rate level in the turbine, even when temperature drops below 20 °C. The additional thermostat

switched the turbines off when temperature was lower than 20 °C. As a result, temperature in the growth room was always within the recommended range of 20 - 26 °C (Fig. 4.2.). Total GDD were calculated using a base temperature of 10 °C.

Plants of variety Silver Haze #9 are sativa-type cannabis plants, resulting in longer stems than is the case with the other, more indica-type plants. Therefore, we pruned tops of Silver Haze #9 plants just before the first flowers emerged, as recommended by Green (2001).

Table 4.1. *Fertilizer schedule applied in the third cannabis growth cycle, based on the Canna ® Terra growth schedule. All products are seized Canna ® products, obtained from the Belgian Federal Police. Weeks are calendar weeks of 2011. – Product was not applied.*

Week	Light (h/day)	Terra Vega (ml/10L)	Terra Flores (ml/10L)	Rhizotonic (ml/10L)	Cannazym (ml/10L)	Cannaboost (ml/10L)	PK 13/14* (ml/10L)
7 – 8	18	20	-	40	-	-	-
9	12	40	-	15	25	-	-
10 – 11	12	-	60	5	25	30	-
12	12	-	55	5	25	30	15
13 – 16	12	-	60	5	25	30	-
17	12	-	-	-	25	30	-

4.2.4. Data collection and processing

By the time that pistils had turned brown, plants were labelled and harvested by cutting the main stem at the bottom of each plant. Plants were subsequently hung upside down to dry in the dark during 7 days. Subsequently, cannabis flowers were clipped, i.e. female flower buds were separated from stem, branches and leaves using scissors. Finally, flowers harvested were weighed per plant using an OHAUS Adventurer^{TM} balance (precision: ± 1 mg). Yield per plant was converted to yield per m² by multiplying per plant yield by 12 and 16 in blocks with 12 and 16 plants per m², respectively.

Prior to analysis of variance, for both experiments, data of each split-plot was randomly divided in 2 parts to add a blocking factor. The latter was necessary since the experimental design contained just two replicates, entailing insufficient degrees of

freedom for analysis of variance. For each block thus obtained per split-plot, average yield per plant and average yield per m² were calculated. Analysis of variance was subsequently done using a nested model in the statistical software package R 3.0.1. Data exploration was done in SPSS 20. For multiple comparison of means between the four levels of the variety factor, the Least Significant Difference (LSD) was manually calculated using the mean square errors obtained in the split-plot analysis of variance (see above). In case interactions between factors density and variety prevailed, multiple means comparison (with the LSD-method) between varieties was done also per whole plot (each with one of the densities under consideration), following Gomez & Gomez (1984).

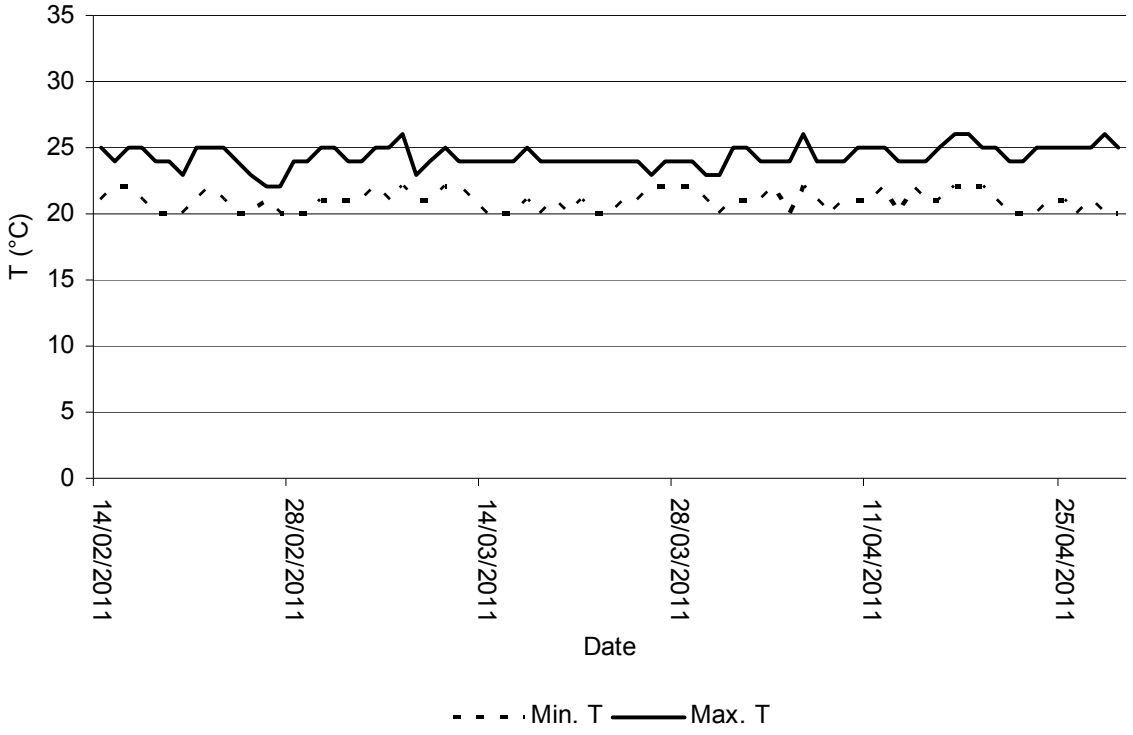


Fig. 4.2. *Daily measured minimum and maximum temperature in de growth room during the third growth cycle.*

4.3. Results

The grow cycle was completed in 11 weeks (or 947 GDD with T_{base} = 10 °C). At harvest, one Big Bud plant and one Skunk #1 plant were found to be stunted. All other 222 plants in the experiment looked normal and had produced a significant amount of consumable cannabis at harvest. Lowest yield (2.7 g) was found with a Big Bud plant, grown at a density of 16 plants per m², whereas highest yield (108.7 g) was found with a plant of variety Skunk #9 which was grown at a density of 12 plants per m². Highest mean yield per plant (62.0 ± 26.6 g) was obtained in blocks with variety Silver Haze #9 at a density of 12 plants per m². Highest mean yield per m² was recorded for the same variety, but grown at a density of 16 plants per m² (917 ± 364 g) (Table 4.2).

Table 4.2. *Average yield of indoor cannabis for each of 8 density x variety factor combinations.*

			Yield (g per plant)		Yield (g per m²)	
Density	Variety	N	Mean	Standard Deviation	Mean	Standard Deviation
12 plants per m²	Big Bud	24	48.1	21.8	578	262
	Skunk #1	24	52.1	22.5	625	270
	Silver Haze #9	24	62.0	26.6	744	319
	X	24	45.8	22.8	549	274
16 plants per m²	Big Bud	31	29.3	20.4	469	327
	Skunk #1	31	35.9	23.3	574	373
	Silver Haze #9	32	57.3	22.8	917	364
	X	32	34.3	14.7	548	235

Data for each factor combination were normally distributed (Kolmogorov-Smirnov test, $p > 0.1$). Analysis of variance (Table 4.3) reveals very significant ($p < 0.01$) differences between varieties for both yield per plant and yield per m², with a significantly higher average yield for variety Silver Haze #9 (59.3 ± 24.4 g per plant; 843 ± 354 g per m²) in comparison with average yield of the other three varieties that are statistically equal amongst them (Table 4.4). Average yield per plant is very significantly ($p < 0.01$) different between plant densities, with highest mean yield found for plants grown at a density of 12 plants per m² (52.0 ± 24.0 g per plant) in comparison with average yield of plants grown at a density of 16 plants per m² (39.3 ± 23.0 g per plant). However, when yield is expressed as g per m², statistical differences between plant densities do no longer prevail. Table 4.3 further shows that

factors variety and density are additive for both yield per plant and yield per m², meaning that there is no interaction between the two factors in their effect on indoor cannabis yield.

Table 4.3. *Results of the analysis of variance of the split-plot experiment on the effect of factors density and variety on the yield of indoor cannabis (third growth cycle). Significance levels of effect or interaction effect at the 0.05 level (*) or 0.01 level (**).*

	Yield (g per plant)		Yield (g per m²)	
	F-value	*p*	*F*-value	*p*
Density	38.9	**0.008	0.1	0.815
Variety	3.6	*0.033	5.2	**0.009
Density * Variety	0.4	0.759	0.7	0.585

Table 4.4. *Main effects of plant density and variety on yield of indoor cannabis and lower bound of the one-sided 95 % confidence interval for the mean yield for each factor level.*

		Yield (g per plant)				Yield (g per m²)			
	N	Mean		Stand. Dev.	Lower bound 1-sided 95 % conf. interval	Mean		Stand. Dev.	Lower bound 1-sided 95 % conf. interval
12 plants m^{-2}	96	52.0	a	23.9	47.9	624	a	287	575
16 plants m^{-2}	126	39.3	b	23.0	35.9	629	a	368	574
Silver Haze #9	56	59.3	a	24.4	53.9	843	a	354	764
Skunk #1	55	43.0	b	24.1	37.5	596	b	330	522
X	56	39.2	b	19.3	34.9	549	b	250	493
Big Bud	55	37.5	b	22.9	32.4	517	b	303	448

For each of the two factors, lower-case letters (a and b) indicate very significant differences (p < 0.001) between means. T-tests were used for comparing means between different plant densities. LSD method was applied for means comparison between varieties.

Across varieties, the lower bound of the one-sided 95 % confidence interval for the mean yield per m² is 575 g per m² and 574 per g per m² for plants grown at densities of 12 and 16 plants per m², respectively.

4.4. Discussion and conclusions

Due to the high variability in cropping systems and varieties, proposing a single, state-of-the-art and reliable figure for the yield of indoor cannabis plantation is no sinecure. Until 2008, jurisdiction in the Netherlands based legal action on yield figures (22 g per plant) proposed by Huizer & Poortman-van der Meer (1995). However, the latter authors used data obtained from seized plantations, where often immature plants are found. Toonen *et al*. (2008) modelled the yield of indoor cannabis plantations based on linear regression using plant density, light intensity and plant development stage reported for 77 confiscated indoor cannabis plantations as explanatory variables. They found that the lower bound of the one-sided 95 % confidence interval for predicted cannabis yield for the median plantation (plant density: 15 per m²; light intensity: 510 W per m²) was 28.1 g per plant. Since 2008, this figure is applied in judicial proceedings in the Netherlands (Weustenraad, 2005), and since 2009 by the Belgian judiciary (Van Camp, 2009). During the past few years, Belgian police frequently seized plantations with plants that bore buds of unquestionably higher weight than 28.1 g per plant, hence the need for the present research (Benny Van Camp, Judicial Commissioner of the DCP; personal communication).

Yield figures reported in this manuscript were obtained via a two-stage approach. At the beginning, we performed three different growth experiments in two different grow cycles with the aim to identify main yield-determining factors in indoor cannabis plantations (chapter 3). It was found that apart from variety, overhead light intensity and plant density play an important role in yield obtained per plant. It was shown that i) yield is higher when plants are cultivated under 600 W lamps in comparison with plants grown under 400 W lamps; ii) some varieties (i.e., in our case Super Skunk and Big Bud) exhibit higher yield than others (White Widow and Northern Lights #5 x Haze); and iii) yield per plant is higher when plants are grown at lower densities. However, when yield is expressed as g per m², no differences in yield were found between the two plant 'densities' we tested. The latter findings, however, can not be explained by a real plant density factor. The effect of plant density in the first two growth cycles was confounded by other factors (pot size and

pot shape). In the first growth cycle, plants at a density of 16 plants per m² were placed in square pots of 11 L, whereas plants at a density of 20 plants per m² were placed in circular pots of 5 L. In the second growth cycle, plants at densities of 12 and 16 plants per m² were placed in square pots of 11 L, and plants with a density of 9 plants per m² were placed in circular pots of 27 L. It was also shown that overhead light intensity and plant density are additive factors, whereas there is a significant interaction between factor variety on the one hand and factors plant density and light intensity on the other.

In a second stage, reported in the present chapter, growth factors and conditions were fine-tuned. Temperature in the growth room was optimized and the vegetative stage (with 18 hours of light) was reduced from 4 weeks (applied in the first two growth cycles, see Tables 3.1 and 3.2) to 2 weeks only, so that photosynthetic assimilation would serve flower bud production more than growth of stem and leaves (Lambers *et al*., 2008; Runkle & Heins, 2006). Overhead light intensity was eliminated as a factor, because it was shown that 600 W lamps generate a significantly higher yield in comparison with 400 W lamps and it is assumed that growers will use lamps that maximize their profit. Moreover, 600 W lamps have an irradiance of 132 W per m² whereas only 79 W per m² is recommended (see § 2.3.2.). As a result, it is also unlikely that higher irradiances will result in higher yields.

Alternative varieties were used and compared with the Big Bud variety, used in the first two growth cycles and which overall gave the highest yields (chapter 3). Lower plant densities (12 and 16 plants per m²) were used in the present study as compared to densities used in the first two growth cycles (chapter 3). Plant density was kept as a factor to verify the claim stated in § 3.4 that differences in yield per plant due to different plant densities no longer occur when yield is expressed as yield per m².

Furthermore, we eliminated statistical confounding of the effect of plant density by pot shape and volume (prevailing in experiments of the first two growth cycles) by using only square, 11 L pots. The factor density was now varied only by providing

more space between pots placed at a density of 12 plants per m² as compared to pots placed at a density of 16 plants per m² (see Fig. 3.14; § 3.2.2.2).

Unlike the design used in the first two growth cycles (chapter 3), the experiment reported in the present chapter included two replicates of each split-plot so that environmental variation between replicates could be taken into account. However, an additional blocking factor (splitting each split-plot into two artificial blocks) had to be added still, to obtain sufficient degrees of freedom that are required for analysis of variance of the split-plot design.

Results confirm that yield per m² does not differ significantly when different plant densities are considered. However, significant differences do occur between different varieties. Whereas in the first two growth cycles (§ 3.3., Tables 3.5 & 3.8), the highest yield figures were obtained for varieties Super Skunk and Big Bud, in the present study, variety Big Bud had the lowest average yield (516.47 g per m²). The latter finding might indicate that variety Big Bud better resists suboptimal environmental conditions, such as those of the first two growth cycles (particularly low temperature). However, as a result of the earlier described improvements to the cultivation protocol, the mean yield figure for the Big Bud variety in the present growth cycle is still higher than the average yield found for the same variety in our earlier experiments (336 g per m² and 401 g per m² in the first, respectively second cycle) (§ 3.3., Tables 3.5 & 3.8). Also, average yield of variety Big Bud in the present study does not significantly ($p < 0.001$) differ from average yield of varieties Skunk #1 and X. Yield of the latter variety, which was obtained from a confiscated illicit indoor plantation, does not differ significantly ($p < 0.001$) from the other varieties (Table 4.4). This would indicate that illicit growers use varieties similar to those that can be obtained from growshops in Amsterdam. When an indoor cannabis plantation is confiscated, there is usually no information on the variety used. Consequently, we think it is necessary to calculate an average yield figure across different representative varieties.

The present study showed that average yield per m² of an indoor cannabis plantation is 624 g and 629 g for plant densities of 12 and 16 plants per m², respectively (Table 4.4). Since during legal proceedings, defence will justifiably argue

that the defendant not necessarily obtained the same mean yield figures found in our research, for police and judiciary purposes, the lower bound of the one-sided 95 % confidence interval for cannabis yield (575 g per m² and 574 g per m² for plant densities of 12 and 16 plants per m², respectively) (Table 4.4) is proposed. Confidence intervals for a certain parameter (in our case indoor cannabis yield per m²) at a level of γ % imply that if the true value of the parameter lies outside this interval once it has been calculated, then an event occurred which had a probability of ≤ (100- γ) % of happening by chance (Cox and Hinkley, 1974). Whereas two-sided confidence limits form a confidence interval, their one-sided counterparts are referred to as lower or upper confidence bounds (Kendall & Stuart, 1973). The lower bound of the one-sided 95 % confidence interval proposed in our study, thus indicates that 95 % of plantations will have a yield higher than the value of the lower bound. As a consequence, the lower bound of the one-sided 95 % confidence interval can be considered as a more conservative estimate of the yield of an illicit indoor cannabis plantation than the mean or median yield (exactly 50 % of all plantations would have a yield below and above the median yield). The same reasoning is behind the yield figure of 28.1 g per plant, presented by Toonen *et al*. (2006), which is the lower bound of the one-sided 95 % confidence interval for predicted yield (by linear regression) of the median cannabis plantation in their study.

For practical reasons, it is fair to conclude from our study results that the yield of 95 % of seized cannabis plantations amounts to at least **575 g per m²**.

Just as in the first growth cycle, the third cycle was completed in 11 weeks, whereas the second growth cycle took 14 weeks to complete. The latter was caused by sub-optimum temperatures. We can safely assume that, under adequate environmental conditions as was the case in our third growth cycle, an indoor cannabis growth cycle (i.e. from rooted cutting to harvest) is completed in **11 weeks** so that **at least 4 growth cycles in one year** can be performed. For research purposes, it might be better to express completion of an indoor cannabis growth cycle in growing degree days (GDD) rather than in a fixed number of weeks. Based on temperature data recorded during the third growth cycle, a cannabis growth cycle could then be harvested at **974 GDD** (with a base temperature of 10 °C). It was found

that some participants on internet cannabis discussion groups claim that the vegetative phase (with 18 h of light and 6 h of darkness) can be skipped for some varieties (e.g Northern Lights #5 x Haze) and that rooted cuttings can immediately be subjected to a light regime that induces flowering (i.e. 12 h of light and 12 h of darkness per day) so that total grow cycle duration would decrease by 2 weeks. Testing of the latter hypothesis is a recommendation for future research on indoor cannabis cultivation. If such a research would reveal that grow cycles can be performed in just 9 weeks (for one, some or all tested varieties), this would mean that at least 5 instead of 4 growth cycles could be performed in one year. The latter would have important implications for police and judiciary that depend on a reliable estimate of the number of growth cycles for accurate calculations of the profits gained during a year of indoor cannabis cultivation.

The only researchers who studied and reported cannabis yield by actually growing the plant are Knight *et al*. (2010) and Potter & Duncombe (2011). In the first study, the Screen-of-Green (ScrOG) method is used. In this approach, a wire mesh is placed on top of the plants to attach their branches to, so that the canopy distributes evenly along the horizontal plane. Using hydroponics with 3 different varieties, researchers obtained per plant yield figures of between 350 g and 1340 g. Such high figures could most probably only be achieved if the wire mesh supports the canopy of one plant under only one assimilation lamp. The authors unfortunately provide no information on the precise cultivation methods (such as plant spacing or density, light intensity, fertilizer application, temperature control, etc.) and used only a limited number of plants (6). Consequently, the results of Knight *et al*. (2010) can not be used as a benchmark for the present study. Potter & Duncombe (2011) cultivated 5 plants of each of 7 cannabis varieties (for details, see § 3.4) under three light intensities (i.e. 270, 400 and 600 W per m²) and at a density of 10 plants per m². They obtained mean yield figures of 422, 497 and 544 g per m² for each of the light intensities, respectively, which is below the lower bound of the one-sided 95 % confidence interval for the yield obtained in our third grow cycle. However, Potter & Duncombe (2011) used varieties other than ours. Since we showed that light and plant density factors interact with variety in their effect on indoor cannabis yield (§ 3.3.1.1), comparison of our study results with those of Potter & Duncombe (2011) is troublesome.

Bedrocan BV (the Netherlands), the official grower of cannabis for medicinal purposes (under the authority of the Ministry of Health, Welfare and Sport, The Hague) obtains an average yield of 315 g per m² and 251 g per m² for two of its main varieties (own breeds) in a similar indoor cultivation setting (details were unavailable) (personal communication from the Bedrocan BV manager). Yield figures of Bedrocan BV are lower than the ones obtained in the present study, but Bedrocan BV focuses in the first place on good-quality cannabis for medicinal purposes and to a lesser extent on yield. The varieties developed by Bedrocan BV were bred by selecting certain quality features such as specific ratios of the active substances, Δ^9-tetrahydrocannabinol (THC), cannabidiol (CBD) and cannabinol (CBN), rather than selecting high-yielding cannabis varieties.

It must be stressed that the presented yield figure of 575 g per m² applies to a 'standard' plantation only, i.e. an indoor plantation with plants in pots filled with peat soil, with lamps of 600 W per m², adequate temperature (20-25 °C), using a 2 week vegetative lighting regime with 18 h of light per day and a 9 week flowering lighting regime with 12 h of light per day, and using a standardized fertilizer schedule (using brands such as Canna, applied in the present study), Aptus, House & Garden, Plagron, or others (see http://www.growcenter-noord.nl/information.php?info_id=16; last visit: 02 December 2013). The yield figures presented in this study also assume cannabis cultivation free of pests (such as spider mites, aphids, trips and/or white fly) or diseases (such as rust (order Pucciniales) or *Fusarium oxysporum*) that may occur in indoor cannabis plantations (Adams, 2007; Green, 2001) and that may eradicate complete plantations (Adams, 2007). Even though indoor plantations with hydroponics systems (i.e. plants root in an artificial medium such as rock wool, expanded clay, vermiculite, etc. to which specifically designed fertilizers are applied) are sometimes discovered by the Belgian Police (exact figures not available), the vast majority of exposed plantations still use 'classic' cultivation methods based on peat soil (Benny Van Camp, Judicial Commissioner of the DCP; personal communication).

Given the more professional character of hydroponics, it can nevertheless be assumed that yield of the latter cultivation system would at least equal yield of cultivation in peat soil. To conclude, it must be mentioned that micro-scale

plantations (one fifth of plantations discovered in Belgium in the 2007 – 2010 period, see § 1.1, Fig. 1.1), with only 2 to 5 plants are probably owned by hobby growers. It is possible that the latter do not achieve the high yields presented in this study because they have no yield-maximizing goal (Decorte, 2010a) and will consequently not always use the (expensive) fertilizer packages or are likely to provide suboptimal temperature and/or lighting regimes.

CHAPTER 5 Financial analysis of illicit indoor cannabis cultivation in Belgium

Adapted from:

Vanhove, W., Surmont, T., Van Damme, P. & De Ruyver, B. (2012). Yield and turnover of illicit indoor cannabis (*Cannabis* spp.) plantations in Belgium. Forensic Science International, 220(1-3), 265-270.

Vanhove, W., Surmont, T., Van Damme, P. & De Ruyver, B. (2014). Filling in the blanks. An estimation of illicit cannabis growers' profits in Belgium. Submitted to the International Journal of Drug Policy (accepted with minor revisions).

5.1. Introduction

When a plantation has been dismantled by the Belgian police and the grower brought to court, the prosecutor tries to make a well-informed estimate of the financial benefits gained by the actors involved. He thereby uses the supposed value of confiscated assets and/or evidence of financial gains resulting from sales of growth cycles prior to the one at the moment of confiscation. For estimation of financial profits, the Belgian police currently relies on data obtained from internet discussion groups on cannabis, the Dutch police and Belgian judicial files. On the latter basis, the price used by commercial cannabis growers is arbitrarily set at € 3 per g cleaned and dried cannabis buds (Van Camp, 2008). However, there is not much evidence on the validity of that figure. Moreover, the Belgian police and judiciary have little knowledge on the price fixing mechanisms in the Belgian cannabis markets. As a consequence, also the price variation at grower level (so-called farm gate price) it is not clear.

In chapters 3 – 4, we shed more light on the agronomic aspects of Belgian indoor cannabis cultivation. It was concluded that i) one cannabis cycle can be completed in 11 weeks so that a grower can theoretically conduct at least 4 cannabis growth cycles in one year; and ii) a reliable yield estimate of an indoor cannabis plantation is 575 g per m² of dried cannabis buds (= lower bound of the one-sided 95 % confidence interval).

Although much is known about wholesale prices and profits in drug markets (EMCDDA, 2012) in general, little is known about precise monetized profit rates of different kinds of cannabis growers. Police and judiciary assume the latter profits are considerably higher than what one can obtain in legal economic activities, but well-informed estimations have never been provided.

As it is, Belgian judiciary currently makes no distinction in prosecution of cannabis plantations of different scales. However, Decorte (2010a, 2010b) argued that small-scale cannabis production should be considered as a specific segment of the Belgian

cannabis market because small-scale-growers i) expect a milder and more organic product than the cannabis sold through mainstream coffeeshop channels; and ii) are so-called ideologically oriented growers who cultivate cannabis as part of a subculture, and do not want to be part of, nor contribute to profits of criminal networks. As a result, Decorte (2010b) makes a case for government-regulated production and trade of cannabis that would limit possible infiltration of organized crime in the cannabis value chain. In this context, scientific research-based data on profit margins for different plantation sizes would at least allow the development of a more fine-tuned and differentiated policy approach towards containing illicit cannabis growing in Belgium.

However, findings obtained in our three indoor cannabis growth cycles (chapters 3 – 4), do not allow us to determine net financial profits of illicit cannabis growers in Belgium. Literature provides no or inadequate information on type of investment made in growing installations nor on other production costs (consumables such as fertilizers, electricity, etc.).

Objectives of the present chapter thus are to i) describe price-fixing mechanisms in the current cannabis value chain, aiming at an updated and legally acceptable unit price for ready-to-use cannabis at the level of the grower (so-called farm gate prices); ii) reveal returns on cost for different types of cannabis growing operations. To the latter end, we will combine information from grey literature resources with findings from real-case studies (i.e. one notorious case of which details were broadly covered by Belgian news media, and three other cases that were selected out of an initial study involving 9 interviewed growers; see § 5.2.1). Ultimately, benefits and return on costs of each selected case of Belgian indoor plantations will be calculated

5.2. Methods

5.2.1. Price setting in the Belgian cannabis distribution chain

Prices and pricing mechanisms in Belgian cannabis market chains were revealed through interviews with actively involved stakeholders (from growers to low-level dealers) who were selected through snowball sampling. The latter implies that respondents recruit future respondents from among their acquaintances, who match the pre-defined characteristics needed to be included in the research sample (Surmont *et al*., 2011). Snowball sampling is an efficient, effective and economic method for gathering data from populations that are difficult to reach (Faugier & Sargeant, 1997; Griffiths *et al*., 1993; Noy, 2007; Sifaneck & Neaigus, 2001). Advantages of snowball sampling include that i) relevant data can be found, irrespective of sample size (Faugier & Sargeant, 1997; Hartnoll *et al*., 1997), ii) qualitative information can be obtained from individuals as well as from the social networks they belong to (Hendricks & Blanken, 1992); and iii) confidentiality is assured, which enhances validity of obtained data (Faugier & Sargeant, 1997).

Fieldwork started in April 2010 and was finalised in January 2011. During this period, 27 respondents were interviewed. They were grouped using a classic four-tier approach (Pearson & Hobbs, 2001), which classifies drug chain actors in 4 groups (i.e. producers and three dealer levels, with lower transaction sizes at lower levels). We thus identified 9 cannabis growers, 8 high-level dealers, 6 middle-market dealers and 4 low-level dealers. Respondents who scored cannabis directly from one or several growers, and had at least two profit-making players underneath them in the distribution chain were characterised as high-level dealers. Those who had at least one market player between them and the grower, and at least one profit-making player underneath them, were characterised as middle-market players. Respondents who sold directly to consumers and had more than two players above them in the chain were characterised as low-level dealers. However, characterization of different players in the cannabis market (Spapens *et al*., 2007) is far more complex than the rough classification used in the present study.

Most studies on pricing mechanisms prevailing in drug markets or, more specifically, in local cannabis markets (Caulkins, 1990, 1994; 1995; 2007; Caulkins *et al*., 1998; Caulkins & Padman, 1993; Caulkins & Reuter, 1996; 1998; Clements, 2004; 2006; Desimone, 2006; Johnson & Golub, 2007; Moeller, 2010; Pacula *et al*., 2007; Reinarman, 2009; Reuter & Kleiman, 1986; Sifaneck *et al*., 2007) are based on quantitative and qualitative data used or produced by the police and/or judicial authorities.

However, the latter are often biased because: i) police investigation methods can be based on stereotypes (certain types of suspects could be neglected since they do not match known suspect profiles, whereby the former may use other pricing mechanisms than stereotype suspects (Caulkins & Padman, 1993; Ponsaers & Bruggeman, 2005; Surmont, 2007; Van Den Broeck, 2001)); ii) unsystematically collected data (Carpentier *et al*., 2008; Caulkins & Reuter, 1996; Johnson & Golub, 2007) (e.g. in Belgium, the police database includes data from customs services in some years, but not in others; or, changes in the police database structure resulted in data loss for the years 2002 and 2004 (Sleiman & Roelands, 2007)); iii) information on drugs in police data is mostly limited to the amount of drugs seized whereas the pricing of these drugs is always derived from interrogations of the arrested grower (Caulkins, 2007) who often report lower prices to avoid higher sentences; iv) police rarely takes the phenomenon of quantity discounting into account (i.e. unit price reduction as transaction volumes rise) (Caulkins, 1994; 2007); and v) data can be influenced by outliers (i.e. extremely high or low prices of cannabis, e.g. when the police confiscates a large quantity of drugs, resulting in a preponderance of lower unit prices due to quantity discounting).

Inconsistencies in quantitative and qualitative research based on police data are the main reasons for choosing a qualitative approach in the present research (Surmont *et al*., 2011). Information gathered in a non-police setting generates more reliable information (Creswell *et al*., 2003). Moreover, police data do not reveal the impact of social relations on pricing mechanisms in illegal markets. Most social relations between different actors in the distribution chain are experienced as relationships based on friendship and/or trust. This implies that some actors might

sell cannabis at more favourable prices than they would to complete strangers with whom they have no affinity (Surmont *et al*., 2011).

In addition to the interviews with cannabis chain actors, 15 judicial files of arrested actors were thoroughly analysed and integrated into the discussion of the qualitative analysis of the interviews.

Snowball sampling was started by recruiting a number of zero-stage respondents, i.e. persons belonging to the pre-existing network of the interviewing researcher. During interviews, respondents were always asked to refer to other possible respondents. Respondents were encouraged to look for respondents who were either above (bottom-up) or below (top-down) themselves in the distribution chain in order to assure that interviews would cover all levels of the cannabis market chain. When the snowball had reached an end, and all contacts derived from the initial zero-stage contacts were exhausted, new potential zero-stage respondents were searched. The latter was done by starting spontaneous conversations with people smoking cannabis at concerts, outside cafés and at summer festivals (*Gentse Feesten*, *Tomorrowland*, *Reggae Geel* and *Maanrock*). One respondent was recruited by posting a message on a social network site on the internet (Facebook).

Price data obtained through snowball sampling will be very heterogeneous because a chain actor can mention various prices depending on specificities of the mentioned transactions (such as level in the value chain, as his/her relation with the buyer, moment of the year, cannabis quality, etc.). As a consequence, statistical analysis of prices could not be performed, because this requires systematic data. Instead, respondents were classified in 5 groups representing value chain levels with different, typical transaction sizes (ranging from 1 g per transaction at retail level to 1,000 g per transaction at grower level) (Bennett and Holloway, 2007). The highest, respectively lowest prices mentioned for each group will be reported.

5.2.2. Cost-benefit analysis of indoor cannabis cultivation in Belgium

5.2.2.1. Case selection

Costs and benefits of four separate (Belgian) cannabis plantation sizes were calculated: three growers (with 5, 150 and 600 plants, respectively) who were interviewed for the study on price fixing mechanisms in the Belgian indoor cannabis sector (§ 5.2.1) and one case of a grower with an industrial-size plantation (> 1000 plants). The latter was not included in the snowball sample of the study on price fixing mechanisms (§ 5.2.1), because these kind of growers are very reluctant in participating in scientific studies of any purpose, because they do not wish to compromise their business (Surmont *et al*., 2011). In all interviews, growers were asked about objectively verifiable data such as number of plants, environmental growth room factors such as temperature and light regime, materials used, etc. In the case of the industrial grower, the latter information was obtained from grey literature and television coverage documenting his plantation at time of seizure.

Several studies have stated that snowball sampling works better with more marginalized groups of drug users (such as heroin or amphetamine users) than with cannabis smokers and dealers, because the latter belong to more socially integrated groups (Korf, 2011; Liebregts, et al., 2011). Nonetheless, we held on to using a snowball sampling approach because i) information given to the police during interrogation by respondents could be highly biased; and ii) the police usually concentrates on arresting stereotypic groups which may bias the sample within a detention setting (Caulkins, 2007; Surmont *et al*., 2011; Van Den Broeck, 2001).

Our intention to discuss monetary transactions did not make interviewing easy, because respondents feared this info might eventually be used against them (Surmont *et al*., 2011). However, we managed to interview nine growers with various characteristics and motives for illicit indoor cannabis growing.

Following the typology of the Belgian Federal Police, one of them held a *micro-plantation* (5 or less plants); one held a *mini-plantation* (6-49 plants); three held a

small-scale plantation (50-249 plants); three others were holding a mid-scale plantation (250-499 plants) and one grower exploited a *large-scale plantation* (500-999 plants). The sample thus adequately represents the Belgian indoor cannabis cultivation sector, as confiscation numbers are more or less evenly distributed over the four grower types (De Ruyver, 2011) (see also Table 1.1).

Three of these nine growers were chosen for more detailed characterization, so that each type was represented in our study. Since the interviews were initially conducted to study pricing mechanisms at different levels of the cannabis distribution chain, it was not self-evident to retrieve detailed information on growing installations and premises. We selected growers that provided us with the most information on their plantation and business. We chose to estimate costs and benefits of the aforementioned industrial grower (approximately 23,000 plants, the largest plantation ever discovered in Belgium), a large-scale grower (600 plants), a small-scale grower (150 plants) and a micro-scale hobbyist grower (5 plants).

5.2.2.2. Cost-benefit analysis

Data on four real growing cases were fed into a financial cost-benefit analysis (Cellini & Kee, 2010). Eide (2000) distinguishes four different cost components of a criminal activity: i) psychic costs (guilt, anxiety, fear, dislike of risk); ii) material costs; iii) expected punishment costs; and iv) opportunity costs. Psychic costs will be omitted from our analysis, because it is not possible to unequivocally monetize them. For material costs, we consider both fixed costs (investments) and variable costs (incurred per growth cycle). Material costs were estimated by using data on the material used in the three growth cycles as reported in chapters 3 and 4. Input prices were obtained from growshop websites or from agricultural supply stores. Expected punishment costs include formal and informal sanctions as well as costs arising from lawsuits. According to Belgian criminal law, cannabis producers risk a fine of between € 1,000 and € 100,000, depending on the severity of nuisance caused by their cannabis growing operations (Van Cauwenberghe, 2012). However, due to the wide range of fines and the many factors that influence the amount of a fine, we did not include the punishment costs in our calculations. Opportunity cost of crime consists of the net benefit (i.e. gross benefit minus costs) of a legal activity foregone

while planning, performing and concealing the criminal act (Eide, 2000). We included labour of the industrial grower in the opportunity costs (see further) but did not consider labour costs for the other three growers as they had a job in (and thus an income from) the legal sector. Free time spent on the plantation should be included in the opportunity costs. However, we do not have any information on the methods, time and number of people involved in plantation set-up or post-harvest trimming activities. Since these can be highly variable (e.g. trimming can be done manually of mechanically), we did not include labour costs for plantation set-up or for post-harvest activities.

In his renowned economic approach to crime and punishment, Becker (1968) showed that the probability of being arrested is an important element in deciding on the marginal utility of criminal activities (see also § 2.4). Rates of return on costs (ROC) of criminal activities, usually defined as net profit (sales minus total costs) divided by total costs, should consequently be adjusted for risk. If the probability of getting caught is π, then the cannabis grower has a probability of (1 – π) of selling a quantity of cannabis Q at unit price P. Following Easton (2004), the rate of return on costs is then:

$$\text{ROC} = \frac{(1-\pi)PQ - C}{C} \quad (5.1) \text{ (see also § 2.4)},$$

in which C is total cost of cannabis growing, and P and Q the price and quantity of cannabis sales, respectively.

Estimation of the value for π in the case of Belgian cannabis production is difficult due to the rapidly changing situation both in terms of total plantation numbers as well as in terms of enforcement. Bouchard (2007) reports a π -value of 0.05 in Quebec, Canada, whereas Easton (2004) assumes a good estimate for π in British Columbia, Canada, to be 0.16. We have no indication of a good estimate for π in Belgium. As a result, we chose to take the average of the aforementioned π-values reported for Quebec and British Columbia. In our basic calculation on ROC of cannabis growing in Belgium, we thus set π to 0.1.

Quantities of commercial cannabis obtained per growth cycle were derived from the overall yield figure determined in chapter 4 (i.e. 575 g per m²) that was multiplied by growth surface area. In two cases, lower yield figures were used (see *infra* for argumentation).

5.2.2.3. Presentation of cases and assumptions made

The analysis spanned a period of 4 growth cycles, which roughly covers one cannabis cultivation year (see chapters 3 – 4). Price information was obtained per case from interviews (see § 5.2.1).

Input quantities and price estimations for each case are summarized in Table 5.1. Where interviews did not yield unambiguous information on the exact nature of inputs used, estimations were made on the basis of extrapolations of input use in the three growth cycles described in chapters 3 and 4. The latter extrapolation was particularly needed in the case of fertilizer consumption rates. Investment costs, variable costs and opportunity costs were adjusted for an inflation rate of 6.16 % (http://nl.inflation.eu/) that occurred during the period between interviews conducted (July 2010) and gathering of cost price information (July 2012), so that all items in formula (1) are expressed in July 2010 prices.

The first case deals with an industrial-size cannabis plantation (around 23,000 plants) that was discovered in 2009 and had been operational for an unknown number of years. It consists of 2 large farming sheds, with a total surface of 1,532 m². Plant pots were not used, as rooted plantlets were planted directly in the soil that covered the shed floor area. The plantation used one 600 W lamp per m², resulting in 1,532 lamps and accompanying ballasts. The plantation consumed (1,532 x 600 W) (lamps) + (25 x 135 W) (ventilators) + (25 x 3000 W) (heaters) + (30 x 550 W) (turbines) = 1,014 kW of electricity. The grower concealed electric power consumption from official power suppliers by generating his own electricity through a diesel generator. Annual fuel consumption of the latter was huge (estimated at 400,000 l per cycle) and required weekly delivery to the farm (thus increasing risk of getting caught). Upon discovery of the plantation, three foreign, illegal workers were found to be working on the plantation. Police reports state (source: newspaper *Het*

Nieuwsblad 15 June 2009) the latter 3 earned € 4,000 per month. As a result, labour cost for one cycle is estimated at € 33.000 per cycle (3 persons x 2.75 months per cycle x € 4,000 per month). During cannabis cultivation, the two large sheds could not be used for any alternative agricultural activities. In order to assess the opportunity cost of this grower, we assume a rental price of € 1,500 per month, which corresponds with rental prices for similar farming sheds (http://www.2dehands.be/ and http://www.aanbod.be/; last visit: 02 December 2013). We further assume the farmer is continuously active in cannabis cultivation and therefore misses a monthly net income of € 1,500 in the legal economy. The latter is an overestimation of the opportunity cost, because according to recent findings of Belgium's largest farmers union, average monthly farmer income is just € 1,190 (Boerenbond, 2013). Total opportunity cost is consequently estimated at (€ 9,000 per growth cycle, i.e. 3 months x € 3,000 per month). Since plant density (8 per m²) is out of the range of the growth experiments reported in chapters 3 - 4, and because of the unusually large scale of the operation under consideration, a conservatively estimated yield of only 300 g per m² is used in the financial analysis instead of the yield figure (575 g per m²) we determined in chapter 4. In the criminological study, it was also shown that cannabis prices decrease with increasing transaction sizes and yield a range of € 3.00 to € 4.25 per g of dry cannabis buds bought at the grower's level. Since cannabis production of the considered grower is estimated at 460 kg per cycle, we used the lower bound of the prices reported further in § 5.3.1 (Table 5.2) (€ 3.00 per g).

The second grower invested in materials to set up a professional, large-scale and soil-based plantation of 600 plants in his basement in 2009. The equipment was bought via a Dutch growshop, but set up by the respondent himself, following guidelines and recommendations from friends, the growshop, internet and various grey literature sources. Because the basement has no alternative economic value and because the grower used his free time (with the help of some friends) to manage the plantation, no opportunity costs are taken into account. Electric power costs were avoided by (illegally) tapping electricity before it came to the meter, a common practice in illicit cannabis cultivation (Bovenkerk & Hogewind, 2002; Spapens *et al*., 2007; Wouters *et al*., 2007). In fact we could view this grower as having two criminal enterprises: i) growing cannabis; and ii) stealing electricity. In order not to credit profits from stealing electricity as profits from cannabis growing, we repeated our

financial analysis (large-scale+ in tables 5.4, 5.6 and 5.7) by taking the electricity cost into account. In the present case, the grower sold lower-quality buds (around 30 %) at € 3.25 per g to the growshop where he sourced his cultivation equipment. Good quality buds (70 %) were sold to a middleman (also connected to the growshop, claiming to operate on behalf of a coffeeshop) at € 3.5 per g. A small (negligible) part was auto-consumed or presented to the friends who helped him with the laborious cutting activities.

The third grower transformed his attic (5 m x 5 m; 20 m² occupied by cannabis plants) into a growth room, in 2007. The equipment was installed by an employee of a Dutch growshop, and although the growshop offered him a 'bargain' (growth room was set up without additional cost in return for the first harvest), he stated to have declined the offer and to have paid for the full installation cost. Presumably, the latter covers the investment cost (as described for the first two growers), supplemented by transport and labour costs. Unfortunately, no information was given on the exact cost of installation, so we only used equipment costs. Following the same reasoning as for the second grower, no opportunity costs are assumed. The respondent has some friends who also had a plantation, and was familiar with the cannabis business, so he did not have many problems in finding a decent contact to sell his stash to. According to the interviewed grower, as a result of his experience (> 5 years), he produces high quality buds that he is able to sell at € 4 per g. As with the second case, a negligible part is auto-consumed or given to friends who assist in harvesting and cutting.

The fourth grower purchased a so-called growth tent (0.9 m x 0.9 m x 1.8 m) in a Dutch growshop, to set up a *micro-scale plantation* to grow 5 plants to fulfil his own needs and those of his closest friends. No opportunity costs are assumed because opportunities missed by investing time and infrastructure in cannabis production are negligible. This grower operates out of the range of the growth experiments reported in chapters 3 - 4, both in terms of plant density (9 to 16 per m² in the latter growth experiments) as in terms of plantation scale (around 200 plants in the latter growth experiments). Furthermore, the interviewed grower claims to strive for quality, rather than for large quantities. As a result, a conservative yield estimate of 300 g per growth cycle was considered for this grower, rather than the yield figure of 575 g per m², proposed in chapter 4. Since profit seeking is not the primary goal of this grower,

the harvest is sold at very 'friendly' prices: € 2.5 per g for small quantities (1 – 10 g) (half of the harvested volume) and only € 2 per g for higher transaction sizes.

Given the uncertainties on the precise yield of the industrial grower (first case), a sensitivity analysis was performed in which yield was varied between 200 and 600 g per m² with an increment of 100 g per m². Growers who operate at a scale similar to those of our case studies might receive different prices because apart from transaction sizes, cannabis price setting also depends on many product- and socially related aspects (see *infra* § 5.4.). As a result, a second sensitivity analysis was performed in which ROC for all considered growers was calculated by varying cannabis prices in the price range reported by respondents (see *infra* § 5.3.1) (€ 3.00 - € 4.25 per g), with an increment of € 0.25.

An important uncertainty in our financial analysis is the probability that Belgian cannabis growers get caught (π). Information on π in Belgian or international cannabis cultivation is scarce. Since π-values reported for Quebec and British Columbia (Canada) vary between 0.05 (Easton, 2004) and 0.16 (Bouchard, 2007) respectively, a third sensitivity analysis was conducted in which ROC for all growers was calculated by varying π between 0.00 and 0.20 with an increment of 0.05.

Table 5.1. *Investments, variable costs and sales prices (1 growth cycle) in € for 4 real cases of Belgian cannabis growers.*

	Unit	Industrial	Large-scale	Small-scale	Micro-scale	Unit price (€)	Price source
Plants	n	23,000	600	150	5		
Surface	m²	1,532	50	20	1		
Investments							
Pots	n	0	600	150	5	0.70	a
Growth tent 1 m²: Secret Jardin Darkroom DR90	n	0	0	0	1	125.00	b
Lamps Philips Master SON-T PIA Plus (600 W)	n	1,532	50	20	1	37.00	b
EB600-SON Electronic Ballasts	n	1,532	50	20	1	60.00	c
Carbon filter Wilco 150 cm; 2400 m³/h	n	30	1	0	0	170.00	b
Carbon filter Can-Light 1500 m³/h	n	0	0	1	0	125.00	b
Carbon filter Can-Light 150 m³/h	n	0	0	0	1	38.00	b
Turbine: Box Silent Air (4250 m³/h)	n	30	1	0	0	295.00	b
Turbine: Box Silent Air (2500 m³/h)	n	0	0	1	0	250.00	b
Turbine: Ruck RK125L 330m³	n	0	0	0	1	75.00	b
Turbine control: Torinsifan (RIC)	n	30	1	1	0	235.00	c
Flexibles	m	350	40	20	0	3.75	b
Reflecting white canvas (2 m wide)	m	0	70	20	0	1.50	b
EUROM EK3301 Heater	n	25	2	1	0	60.00	d
Honeywell NV-1800E Ventilator	n	25	2	2	0	30.00	b
1568 kW Diesel Generator Set (380/220 V)	n	1	0	0	0	310,200.00	e
Trimprol Automatic Cannabis Cutter	n	1	0	0	0	1,950.00	b
Variable costs							
Rooted plantlets	n	23,000	600	150	5	2.00 / 10.00	f
Peat soil	l	0	6,600	1,650	55	6.50	g
Tap water	m³	0	20	5	0	3.05	h
Well water	m³	782	0	0	0	1.80	i
Electricity from the net	kWh	0	30,240 *	12,096	605	0.24	j
Diesel for power generator	l	285,264	0	0	0	0.77	k
Terra Vega	l	617	17	5	0	6.00	b
Terra Flores	l	3,081	81	21	1	4.75	b
Rhizotonic	l	0	27	7	0	18.50	b
Cannazym	l	0	43	11	0	10.00	b
Cannaboost	l	0	46	12	0	35.00	b
Labour	hours	1,848	0	0	0	6.00	b
Opportunity costs							
Rent of sheds	months	3	0	0	0	1,500	
Income in legal economy	months	3	0	0	0	1,500	
Sales price	€ / g	3	3.43 °	4	2.25 †		

** Electricity not paid for, because tapped before the meter; ° price composed of 30 % € 3.25 g^{-1} and 70 % € 3.5 g^{-1};* † price composed of 50 % € 2 g^{-1} and 50 % € 2.5 g^{-1}; a = ALTCO BVBA, Assenede, Belgium; b = Growcenter-Noord (Amsterdam, NL) (http://www.growcenter-noord.nl/); c = Growshoponline (Heerlen, NL) (https://www.growshoponline.nu/); d = Wehkamp, Zwolle (http://www.wehkamp.nl); e = price (VAT incl.) for a Himoinsa™ generator, model HMW-1785 T5 at Van Daele Machinery, Belgium (http://www.vandaele-machinery.be/, 395 l/h diesel consumption at full power; f = Police reports consistently mention € 10 per cutting; for the industrial grower, however, quantity discounts are expected and € 2 per cutting is used (based on prices offered for cuttings on internet forums such as http://www.jointjedraaien.nl/ or http://www.wietforum.nl/); g = AVEVE (http://www.aveve.be); h = Water-Link (http://www.water-link.be/), prices consumption between 15 - 500 m³, prices for 2012, incl. VAT; i = cost estimate of well water in Flemish agriculture, including pump and distribution infrastructure depreciated over 10 years and taxes (Messely *et al*., 2008); j = Luminus (https://www.luminus.be/), only daytime rate, incl. all taxes, using IMEWO distribution net, incl. VAT; k = Belgian Federal Government. Directorate-general Statistics and Economic information (http://statbel.fgov.be), average 2008 price for fuel oil supplied at quantities > 2,000 l. Last visit to all cited websites: 02 December 2013.

5.3. Results and discussion

5.3.1. Prices

Prices reported in Table 5.2 are minimum and maximum prices mentioned by respondents for different cannabis transaction sizes in Belgium in the second half of the year 2010. Respondents mentioned prices they i) applied at their own level in the distribution chain; ii) mentioned their business associates used at other levels; and/or iii) used to apply when they operated at a different level in the distribution chain. It was found that actors at a given level sell cannabis in different transaction sizes and that price differentiation is not made according to chain actor but rather according to transaction size. High-level dealers who generally sell in kilos or 500 g packages were in some cases also found to sell packages of 25 g to friends or well-known clients. Unit prices for high transaction sizes (> 1 kg, typical for growers and high-level dealers) vary between € 3.00 and € 4.25 per g and increase with decreasing transaction sizes (1 g, typical at retail level), sold at between € 7.00 and € 8.00 per g (Table 5.2).

Table 5.2. *Minimum and maximum prices (in €) per g of cannabis, mentioned by respondents (N=27) according to different conventional transaction sizes (more than one price statement per respondent is possible) in Belgian cannabis value chains.*

Conventional transaction size (g)	Price per g (€)	
	Minimum	Maximum
1000	3.00	4.25
500	4.00	6.00
100	4.50	6.50
25	6.60	8.00
1	7.00	8.00

At grower level some price-fixing mechanisms, applied while bargaining over a transaction between actors, were identified: i) dry buds were considered a better deal than moist buds since the latter lose weight and consequently value, along the distribution chain; ii) complete buds can yield a higher sale price than ground buds since the latter risk to be mixed with sand, grass and other materials used for adding weight to a package of cannabis; iii) potency (defined as % of THC in dried female

flower buds) also affects price: higher potency automatically generates a higher sale price than lower potency crops. In practice, potency is not lab-tested, but evaluated by the buyer who will usually smoke a small sample of the traded cannabis buds. Aforementioned criteria are also applied at other levels of the distribution chain, where they can cause considerable price variation. However, we did not find any indications showing that cannabis variety affects price setting. The latter has been documented to occur in Dutch coffeeshops, but was not proven for the Belgian market.

Prices found through snowball sampling were confirmed in judicial file analysis. Prices at grower level and for high-level dealers reported in judicial files (Table 5.3) correspond with prices mentioned by respondents. Judicial files on low- and middle-level chain actors were not found.

Table 5.3. *Minimum and maximum prices (in €) per g of cannabis, found in 15 judicial files of offenders at different levels of the Belgian cannabis value chain (more than one price statement per file is possible).*

Level	Price per g (€)	
	Minimum	Maximum
Grower level	3.00	4.00
High level	4.00	6.00
Middle market	5.00	7.00

5.3.2. Profits and return on costs

Total investment cost of the first (industrial) grower needed for covering the 1,532 m² plantation can be estimated at € 510,747 (Table 5.4). Variable costs per 11-week cycle, including purchasing rooted plantlets, and costs for electricity and fertilizers, can be estimated at € 381,808. Aggregated opportunity costs for the considered grower amount to € 8,478 per cycle. When using a yield figure of 300 g per m², total yield of one cycle can be estimated to be 459,600 g or around 460 kg.

After one production year (4 cycles), total costs are estimated at € 2,081,890 whereas total (adjusted) gross benefit (defined by (1-π)PQ, see (1)) is € 4,963,680 and ROC is 1.4. Sensitivity analysis (Table 5.5) shows that when the conservative

yield estimate of 300 g per m² is increased to 600 g per m² (slightly higher than the yield figure proposed in chapter 4), benefit of the industrial grower (after 1 year) increases to € 9,927,360 and ROC to 3.8.

For the large-scale grower, total investment cost was estimated to be € 7,727. Variable costs were estimated to be € 9,369 per cycle. Using the yield figure of 575 g per m², this respondent could generate a possible yield of 28,750 g per cycle. When selling 70% of his harvest to a broker at € 3.5 per g and 30% to a growshop at € 3.25, this would generate a possible total benefit (after one year and adjusted for the chance of getting arrested, π) of € 354,488 and an ROC of 6.8. In reality, this figure will probably be less: a part of the harvest was paid to the cutters in kind. Tapping electricity before the meter seriously reduced his variable costs. If he was paying for electricity (large-scale+), as might be the case with many growers of similar size, € 7,258 would be added to the variable costs each cycle. However, even in that case, ROC after one year would be high and in the range of 3.8.

Based on our calculations, total investment cost of the small-scale grower should have been around € 3,391. This respondent was well-aware of the large profits he would generate. As a result, he did not find it necessary to tap electricity illegally before the meter. In contrast to The Netherlands, Belgium has not yet set up any agreements with electricity companies, to alert judicial authorities in case of unusual high consumption of electricity (Van Camp, 2008). So, as the grower paid electricity bills just as any citizen, variable costs per cycle would have reached € 5,108 of which € 2,903 only for electricity. Using the yield figure of 575 g per m², the plantation could have generated 11,500 g of dried cannabis buds per cycle. The respondent strived to produce a high quality product and had a fixed agreement with his buyer to be paid € 4 per g. After one year (four cycles), this would generate a total benefit (adjusted for the chance of getting arrested, π) of € 165,600 and a ROC of 6.0. The small amounts of stash consumed by the grower and/or paid to his cutter/friends, are negligible and do not significantly affect total benefit.

Following our estimations, initial investment of the micro-scale grower was € 352. Variable costs to produce a harvest-ready first cycle are estimated at € 215. Using a modest yield estimate of 300 g per m², his first cycle supplied him with 300 g of dried

buds of cannabis. Not being a profit seeker, he gave some of the harvest away to his friends for free and sold a further part of it to other friends, using low retail prices of between € 2 and € 2.5 per g. Considering that the grower sold all his crop at an average retail price of € 2.25 per g, he would generate a total benefit of € 4,590 (adjusted for the chance of getting arrested, π) and an ROC of 2.8 after one year (4 cycles). In real life, the profit was (according to the respondent) € 0, because he used a part of the crops for self-supply, and shared or gave away another part, selling only a small part (thereby continuously varying the retail price between € 0 and € 2 per g) to break-even.

Table 5.4 – *Financial analysis of 4 real cases of Belgian cannabis growers after one year or 4 cycles of cannabis growing. Large-scale+ takes the electrical power costs of the large-scale grower into account.*

Grower type	N° of plants	Crop area (m²)	Fixed costs (€)	Fixed costs per m² (€)	Variable costs (€)	of which power costs (€)	Variable costs per m² (€)	Total costs (€)	Total costs per m² (€)	Total gross revenue (€)	ROC (1 year)
Industrial	23,000	1,532	510,747	333	1,527,233	1,226,332 (80 %)	997	2,081,890	1,352	4,963,680	1.4
Large-scale	600	50	7,727	155	37,477	0	750	45,204	904	354,488	6.8
Large-scale+	600	50	7,727	155	64,823	29,032 (45 %)	1,296	72,550	1,451	354,588	3.9
Small-scale	150	20	3,391	170	20,431	11,612 (57 %)	1,022	23,822	1,191	165,600	6.0
Micro-scale	5	1	352	352	858	580 (68 %)	858	1,211	1,211	4,590	2.8

Comparison of data with that of other findings elsewhere is difficult due to the scarcity of studies on the subject. Cervantes (2006) estimates total costs of two real-case Dutch indoor cannabis plantations to be € 356 per m² for a 12 m² plantation and € 492 per m² for a 24 m² plantation. Caulkins (2010) estimated total costs of three typical cannabis plantation sizes in the United States. Cost estimates were € 988 per m² for a small-scale (2.3 m²) plantation, between € 904 and € 1,808 per m² for a mid-scale plantation (140 m²), and between € 158 and € 486 per m² for an industrial plantation (4,000 m²) (all prices in this section were converted from US$ using a conversion factor of 0.75). According to Caulkins (2010), the lower costs mentioned by Cervantes (2006) are probably linked to the location of the studied plantations in The Netherlands, where material for cannabis growing infrastructure is more easily and more abundantly available at lower costs.

Contrary to the costs mentioned by Caulkins (2010), in the present study no significant economies of scale (i.e. lower costs per m² with larger scale of operation) were elucidated. Lowest fixed costs per m² were found for the large-scale grower (€ 155), whereas fixed cost per m² for the industrial and micro-scale grower was more than double that amount (€ 333 and € 352, respectively) (Table 5.4). Variable costs per m² were highest for the small-scale grower (€ 1,022) and for the large-scale grower, taking the electricity cost into account (large-scale+ in Table 5.4). Electricity costs vary from 45 % (large-scale+ grower) to even 80 % (industrial grower). As a result, stealing electricity by tapping it before the meter, considerably reduces costs of indoor cannabis growing. Absence of economies of scale in our study might be due to the absence of labour costs (and/or opportunity cost of the free time spent in the plantation) in our financial analysis. However, as explained in § 5.2.2.2, verification of these costs was not possible based on our interview data.

Table 5.5. *Sensitivity analysis of 1 year of cannabis growing by an industrial grower (profile 1: 23,000 plants on 1,532 m² of cultivation surface).*

Yield (g per m²)	Total cost (€)	Price per g (€)	Total gross revenue (€)	π	ROC (1 year)
200	2,071,890	3.00	2,309,120	0.1	0.6
300	2,071,890	3.00	4,963,680	0.1	1.4
400	2,071,890	3.00	6,618,240	0.1	2.2
500	2,071,890	3.00	8,272,800	0.1	3.0
600	2,071,890	3.00	9,927,360	0.1	3.8

Our financial analysis shows that in all considered cases, ROC is positive after the first growth cycle, even when assuming that all fixed costs are incurred before the first cycle starts. In Belgium, in 2010 mean annual per capita income was € 15,598 (Source: Belgian Federal Government. Directorate-general Statistics and Economic information (http://statbel.fgov.be). It was shown that small-scale, large-scale and industrial growers generate profits that are far above the domestic average income level. Moreover, ROC values are considerable. Across the four cases, ROC values are lowest for the industrial grower (1.4) and the micro-scale grower (2.8). However, these profit margins are greatly exceeded by ROC values of the large-scale and mid-scale growers, which are at respectively 6.8 and 6.0. When electricity costs for the large-scale grower are taken into account (large-scale+), ROC reduces to 3.9 (Table 5.4).

Sensitivity analysis in which sales prices are modulated in the range of € 3.00 and € 4.25 per g of dried cannabis buds shows that the divide between large- and small-scale growers with very high profit margins on the one hand, and the industrial and micro-scale growers with smaller, but still considerable ROC values, on the other hand, is maintained in the considered price range (Table 5.6). The micro-scale grower nevertheless differs from the other cases because the latter respondent claims to seek no profit from his growing operations, a typical characteristic of small-scale growers, according to Decorte (2010a). Nonetheless, results show that even with this kind of micro-scale plantation, high profits can be generated. The grower in this case can be considered to be both a grower and a retail seller. When this grower with 5 plants would be a real profit seeker and sell all harvested cannabis at retail prices (currently between € 7 and € 8) (Vanhove *et al*., 2012), he could generate a possible profit ranging between € 7,560 (ROC 5.2) and € 8,640 (ROC 6.1) over one year. The latter ROC values are in the range of ROC values for both the large- and the small-scale grower in the sensitivity analysis.

Table 5.6. *ROC in a sensitivity analysis of 1 year of cannabis growing by 4 grower profiles, using different sale price levels. Large-scale+ takes the electrical power costs of the large-scale grower into account. *Gross revenue is adjusted for the probability of getting arrested (π).*

Price (€ per g)	Industrial	Large-scale	Large –scale+	Small-scale	Micro-scale
	Total Gross Revenue (€)*				
3.00	1,240,920	77,625	77,625	31.050	810
3.25	1,344,330	84,094	84,094	33,638	878
3.50	1,447,740	90,563	90,563	36,225	945
3.75	1,551,150	97,031	97,031	38,813	1,013
4.00	1,654,560	103,500	103,500	41,400	1,080
4.25	1,757,970	109,969	109,969	43,988	1,148
	Total Costs (€)				
all prices	2,081,890	45,204	72,550	23,822	1,211
	π				
	0.1	0.1	0.1	0.1	0.1
	ROC				
3.00	1.4	5.9	3.3	4.2	1.7
3.25	1.6	6.4	3.6	4.7	1.9
3.50	1.8	7.0	4.0	5.1	2.1
3.75	2.0	7.6	4.4	5.5	2.4
4.00	2.2	8.2	4.7	6.0	2.6
4.25	2.4	8.7	5.1	6.4	2.8

In our basic analysis, we assumed the probability of getting arrested as a cannabis grower in Belgium (π) to be 0.1. The precise value of π, however, is a major uncertainty in the present study and proves to be significantly influencing ROC values, as shown by the sensitivity analysis in which π is decreased to 0 (no chance of getting arrested), as well as increased to 0.2 (20 % chance of getting arrested). Results (Table 5.7) show that even at high values for π (0.2), ROC for the large-scale, large-scale+ and the small-scale farmers remains high (6.0 and 5.2, respectively) and is still > 1 for the industrial (1.1) and the micro-scale grower (2.4).

Sensitivity analysis of the ROC was only performed for the industrial grower (Table 5.5). The large-scale as well as the small-scale grower operate at a scale (150 – 600 plants) similar to that of the agronomic experiments described in chapters 3 – 4. For these growers we decided to use the most reliable yield estimate (575 g per m²) as presented in § 4.4. For the micro-scale grower, a conservative yield estimate of 300 g per m² was assumed because this (hobby-)grower produced cannabis less intensively (see § 5.2.2.3). Application of the mean yield figure (625 g per m²) obtained in our agronomic experiments (§ 4.3., Table 4.4), instead of the lower bound

of the one-sided 95 % confidence interval (575 g per m²), in the financial analysis of all growers, would not considerably affect ROC for the large-scale (7.5 instead of 6.8), the large-scale+ (4.3 instead of 3.9) and the small-scale (6.6 instead of 6.0) growers. For the micro-scale grower, however, increasing yield to 625 g per m² would imply a considerable increase in ROC (from 2.8 to 6.9). However, obtaining such a high yield is very unlikely in the specific growth setting used by the micro-scale grower (see § 5.2.2.3).

Table 5.7. *ROC in a sensitivity analysis of 1 year of cannabis growing by 4 grower profiles, using different levels of π. Large-scale+ takes the electrical power costs of the large-scale grower into account.*

π	Industrial	Large-scale	Large –scale+	Small-scale	Micro-scale
	Price per g (€)				
	3.00	3.43	3.43	4.00	4.25
	Total Gross Revenue (€)*				
0.00	1,378,800	98,469	98,469	46,000	1,275
0.05	1,309,860	93,545	93,545	43,700	1,211
0.10	1,240,920	88,622	88,622	41,400	1,148
0.15	1,171,980	83,698	83,698	39,100	1,084
0.20	1,103,040	78,775	78,775	36,800	1,020
	Total Costs (€)				
all π-values	2,081,890	45,204	72,550	23,822	1,211
	ROC				
0.00	1.7	7.7	4.4	6.7	3.2
0.05	1.5	7.3	4.2	6.3	3.0
0.10	1.4	6.8	3.9	6.0	2.8
0.15	1.3	6.4	3.6	5.6	2.6
0.20	1.1	6.0	3.3	5.2	2.4

5.4. Conclusions

Research on prices and price-fixing mechanisms in the Belgian cannabis market chain by means of snowball sampling, has a number of limitations. The technique is very time-consuming (Decorte *et al*. 2003; Decorte & Tuteleers, 2007; Hartnoll *et al*., 1997; Maalsté, 2008; Noy, 2007). Sampling and interviews in the present research were performed by only one researcher. As he started from his personal social network, it might be presumed that respondents share characteristics with the interviewer and that the respondents the latter referred to share the same characteristics with zero-stage respondents. This bias has been explained in more detail in other snowball sample research on players in the cannabis market in Belgium (Decorte *et al*., 2003; Decorte & Tuteleers, 2007). In the present study, this bias was limited to a certain extent since the researcher had already been involved in other cannabis research projects and thus had multiple networks to source from (Surmont, 2007), leading to a more diverse sample (Maalsté, 2008). The specific nature of the research population and the methodology used (snowball sampling) nevertheless resulted in a limited sample size (27 respondents) and heterogeneous price data. As a consequence, we were unable to perform thorough statistical analysis of prices mentioned by respondents.

Results of interviews and judicial file analysis showed that i) unit prices are predominantly determined by transaction sizes; but ii) a set of product- and socially related price-fixing mechanisms have an equally important role. As a result, it is not possible to present a conclusive price value for cannabis at different levels of the Belgian cannabis market chain. Table 5.2 shows that growers receive between € 3.00 and € 4.25 per g of dry cannabis buds, and that the value currently used by the Belgian judiciary (€ 3.00 per g) would consequently represent an underestimation in most cases.

Growth experiments confirmed that one cannabis cycle could be completed in 11 weeks. As a result, a grower can theoretically conduct at least 4 cannabis cycles during one year. It was shown that a confident yield estimate of an indoor cannabis plantation is 575 g per m². An illicit Belgian cannabis grower will consequently gain a

gross revenue of between € 6,900 and € 9,775 per m² per year (€ 3.00 or € 4.25 per g x 575 g per m² x 4 cycles per year).

The financial analysis clearly shows that returns on costs for all scales of indoor cannabis cultivation are considerable and are generated over a short period of time (in all cases, ROC is > 1 already after a first growth cycle of 11 weeks). The financial analysis spans only one year just to show that in such a short term, returns on costs for all scales of indoor cannabis cultivation are considerable (apart from the industrial case, ROC is > 1 already after a first growth cycle of 11 weeks). If we would extend the timeframe of our analysis to two or four years, returns on costs would even be greater, because most investments (e.g. lamps) can not be amortized over just one year.

Sensitivity analysis shows that the latter conclusion is robust so that it can be generalized for all cases of indoor cannabis cultivation in Belgium. The sensitivity analysis further shows that ROC values are more sensitive to different prices than to different degrees of the risk of getting caught (π). However, price is a more certain parameter than π in our study, because price data used in our analysis is (apart from the industrial grower case) based on interviews with the respective growers, whereas π-values were varied in a range defined in studies on cannabis production in Canada (Bouchard, 2007; Easton, 2004). Demand, supply and police focus and efforts might be considerably different in Canada as compared to Belgium. As a result, π remains the most uncertain parameter.

If police would shift its focus away from micro-scale growers who, according to Decorte (2010a), represent mostly non-profit seeking hobby growers, and intensify efforts to confiscate large-scale and industrial scale plantations, π-values would be reduced for the micro-scale growers and be increased for the larger scale growers. Our sensitivity analysis shows that even in case of such differentiated police efforts, large- and small-scale plantations would still remain the most profitable. However, the consistency in total costs per m² across growers (Table 5.4) indicate that differences in ROC between large- and small-scale plantations on the one hand and micro- and industrial scale plantations on the other hand, are predominantly linked with variation in yield and price, rather than with cost per unit area.

Because of the criminal networks that are often behind small- to industrial-scale plantations, concentrating on professional (industrial) cannabis cultivation is a high-ranked priority in the security policy agendas of Belgium and the Netherlands. The enormous profit perspective is the driving force behind the illicit drug economy. As shown in this chapter, profits are determined by sales prices, production costs and methods, and by the risk of getting arrested. Criminal organizations that control cannabis production can only be dismantled successfully only when their profits can be seized and confiscated.

The large return on costs evidenced in the present study, illustrates the relevance to confiscate these illicit profits. Production is the first and thus most important link in the cannabis supply chain. The EMCDDA tries, at European level, to develop reliable indicators in order to be able to monitor the supply side, as they currently do for the demand side. EMCDDA is currently substantiating drug supply indicators in three main fields: drug markets, drug-related crime and drug supply reduction efforts (Carpentier, 2012). Findings of the present research provide an important qualitative and quantitative set of tools to evaluate the reliability of the developed or proposed indicators. These insights form the cornerstones of an integral and integrated response to drug-related societal problems, as implemented in a lot of European countries (Muscat *et al*., 2012).

CHAPTER 6 General conclusions and recommendations

6.1. General conclusions

Belgian police and judiciary currently base seizure of profits of indoor cannabis on unreliable and outdated data on yields and prices. Our research addressed these problems first of all by setting up a cannabis plantation that resembles a typical real-case indoor cannabis plantation in terms of size, varieties used and environmental conditions applied. In the growth room, especially designed for our research, we successfully performed three cannabis growth cycles: i) 20 May – 30 July 2010; ii) 30 September – 30 December 2010; and iii) 14 February – 29 April 2011. With each growth cycle we obtained higher average yields both per plant as per m², which indicates that experience of the grower is in important factor in obtaining relevant cannabis yields.

From the results of the growth experiments, it can be concluded that yield of indoor cannabis is primordially determined by plant density, intensity of the assimilation lamps and variety used. Furthermore, significant interaction effects occur between the latter factors. THC-content of indoor cannabis, however, does not depend on any of the considered growth factors apart from variety.

If only the most commonly used light intensities (i.e. assimilation lamps of 600 W and 1 lamp per m²) are considered, yield, expressed as weight per plant of dried female flowers (cannabis buds) is determined by both variety and plant density. However, if yield is expressed per surface unit, significant differences in yield between different varieties are evidenced, whereas those between different plant densities no longer prevail.

Using a sample of unknown provenance (i.e. variety X) in our third growth cycle as a control check on what is really going on in Belgian illicit indoor cannabis plantations, it was concluded that the varieties used in the latter growth cycle realistically cover varieties commonly used by indoor cannabis growers in Belgium. On the latter basis, it can be concluded that a realistic yield estimate of a Belgian indoor cannabis plantation is 575 g per m² (i.e. the lower bound of the one-sided 95 % confidence interval). This means that reliable yield estimates per cannabis plant

can be more realistically set at 36 g and 48 g for plants at densities of 16 and 12 plants per m², respectively. Instead of using the average yield of an Belgian indoor cannabis plantation we obtained in our experiments (627 g per m², i.e. 39 g and 52 g per plant for plant densities of 16 and 12 plants per m², respectively), we propose the application of the lower bound of the one-sided 95 % confidence interval (575 g per m²) as a more conservative measure. The latter is important to avoid future criticism by the court case defence attorney of illicit indoor cannabis growers who might correctly state that many growers will obtain a yield below our average level.

Yield figures presented in this study as a reliable measure for calculating profits gained by illicit indoor cannabis growers, were obtained in a cannabis growth cycle that was set up according to state-of-the art practices, was performed free of pests and diseases and in the absence of anomalous events such as interruption of the light regime or temperature shocks. In case offenders in court have proof of such irregularities, yield figures we present in this study might be disputed as a valid measure for yield and profit calculation.

Suboptimal fertilization can reduce yield by one third. It was also found that significant interaction effects with variety occur, meaning that yield reduction resulting from suboptimal fertilizer application will differ depending on variety used. However, the latter finding is not built on firm ground because it resulted from an experiment in the second growth cycle that was characterized by high levels of withered plants (43 % in the experiments with reduced fertilizer levels) and suboptimal temperature. Since growth schedules are straightforward and fertilizers are widely, and legally, available in so-called growshops, it is very unlikely that semi-professional, illicit growers would inadequately apply plant nutrients.

Under optimum growth conditions, it is possible to complete an indoor cannabis growth cycle (i.e. from planting of cuttings to harvest) in 11 weeks. If it is assumed that growth cycle preparation (rooting of cuttings) and post-harvest activities (drying and clipping of cannabis flower buds) can be completed while other growth cycles are ongoing, at least 4 (theoretically 5) indoor cannabis growth cycles can be performed in one year.

Based on interviews with 27 representative stakeholders in the Belgian cannabis sector, it was found that cannabis sales price at grower level ('farm gate' unit price) varies between € 3 and € 4.25 per g. The latter results are backed by judicial file analysis. Our criminological research did not, however, reveal any price differentiation following the different cannabis varieties cultivated in cannabis plantations. Cannabis prices seem to depend largely on transaction sizes. It is fair to assume that lowest prices occur at grower level, since it is the first link in the indoor cannabis value chain and because transaction volumes are usually high. It is, however, very difficult to propose a general cannabis sales price that could be used in Belgian judiciary for calculation of an illicit indoor grower's profits. Cannabis prices depend to a large extent on a set of product- and socially related mechanisms such as the nature of the network the grower is involved in (purely Belgian or with involvement of Dutch OCGs) and social relations between the grower and his buyers.

Growers at any scale of production (ranging from 5 up to 23,000 plants) obtain high profits in a very short time. The largest grower in our analysis (23,000 plants) had a total benefit of almost 5 million euro after 1 year, with a rate of return on costs of 1.4. Highest rates of return on costs, however, are obtained by large- (600 plants, ROC = 6.8) and small-scale (150 plants, ROC = 150) growers. Confiscation of these high and quickly gained profits is an important element in adequate control of criminal activities linked with indoor cannabis cultivation, as it prevents investment of profits in similar or other criminal activities.

Although micro-scale growers (≤ 5 plants) also have potentially large rates of return on costs, our own interview results concur with findings of Decorte (2010a; 2010b) that these micro-scale growers form a separate segment in the cannabis sector. They grow cannabis more as a hobby rather than as an income-generating activity and will usually consume much of the cannabis harvest themselves or give large parts away to friends. In 2010, around 20 % of confiscated cannabis plantations in Belgium consisted of micro-scale growers (Table 1.1), which shows that the latter growers can not be neglected in drug policies. The latter should consequently be differentiated and focus on larger-scale cannabis growers, since these are more likely to be linked with organised crime, whereas they also generate larger profits (in absolute terms).

6.2. Recommendations

6.2.1. Implementation of research results

In light of the results obtained in the present study, at confiscation of soil-based indoor cannabis plantations, police intervention staff should at least record:

i) total number of plants;
ii) the surface covered with plants (m²);
iii) the number of assimilation lamps per m² (by counting the number of lamps and dividing it with growth surface); and iv) the power of the lamps (in W per lamp).

These data will allow verification of whether the plantation had been established according to the standard situation assumed in our study, i.e. with a light intensity of 600 W per m² and a plant density ranging 12 - 16 plants per m².

Some examples of yield and turnover calculations.

1. A cannabis plantation is discovered in a shed. Around 1,000 plants were found on a total growth surface of 56 m² (7 m x 8 m) and light density is at one 600 W lamp per m². This yields:
    - plant density: 1000 plants on 56 m² = +/- 18 per m² (i.e. within the range described in our study);
    - yield per cycle: 56 m² x 575 g per m² = 32.2 kg;
    - yield per year (provided that growth conditions are 'standard' and that the plantation was run continuously over a one year period): 32.2 kg per cycle x 4 cycles per year = 128.8 kg;
    - annual turnover: 128,800 g x € 3 per g (minimum price) or € 4.25 per g (maximum price) = € 386,400 - € 547,400.

2. In an attic of a residential house, a cannabis plantation is discovered with 350 plants, cultivated on an area of 25 m² (5 m x 5 m). Lamps were 1,000 W lamps that were placed at regular distances (1.25 m x 1.25 m) over the whole growth surface;
    - plant density: 350 plants on 25 m² = 14 per m² (i.e. within the range described in our study);
    - light density: 16 lamps / 25 m² = 0.64 per m²; lamps are 1000 W lamps, however, so that yield figures proposed in this study can be reasonably used because power can be recalculated at 640 W per m²;
    - yield per cycle: 25 m² x 575 g per m² = 14.375 kg;
    - yield per year (provided that growth conditions are 'standard' and that the plantation was run continuously during one year): 14.375 kg x 4 cycles per year = 57.5 kg;
    - annual turnover: 57,500 g x € 3 per g (minimum price) or € 4.25 per g (maximum price) = € 172,500 - € 244,375.

3. In a farm shed, a cannabis plantation with 2,000 plants on a surface of 250 m² (25 m x 10 m) is discovered. Lamps were 600 W that were placed at a density of 1 per m²;
    - plant density: 2,000 plants on 250 m² = 8 per m² (i.e. below the range assumed in our study);
    - as a result, the yield estimate of 575 g per m² can not be used;
    - our study showed that per plant yield increases with lower plant densities;
    - as a result, it is safe to assume that per plant yield at densities < 12 per m² will at least equal the assumed per plant yield obtained at a density of 12 plants per m² (i.e. 48 g);
    - yield per cycle: 2,000 plants x 48 g per plant = 96 kg;
    - yield per year (provided that growth conditions – other than plant density - are 'standard' and that the plantation was run continuously during one year): 96 kg x 4 cycles per year = 384 kg;
    - annual turnover: 384,000 g x € 3 per g (minimum price) or € 4.25 per g (maximum price) = € 1,152,000 - € 1,632,000.

6.2.2. Deviations from the standard situation

In the present study, we have frequently claimed that the proposed yield figure of 575 g per m² is only valid for 'standard' plantations, i.e. with infrastructural, environmental and agronomic characteristics that concur with those of our third growth cycle (see chapter 4). The proposed yield figure of 575 g per m² can not be used in case:

- plants (at any density) are placed in pots that significantly differ both in volume and shape from the standard pots we used in our (third) growth cycle (i.e. square 11 L pots);
- plant densities are lower than 12 plants per m² or higher than 16 plants per m². If plant densities are lower than 12 plants per m² and all other growth factors correspond with those from our study (third cycle, chapter 4), the yield figure of 48 g per plant (valid for a density of 12 plants per m²) can still be used to calculate yield (at a per plant basis) of the plantation, because we showed that lower plant densities result in a significantly higher yield per plant in comparison with higher plant densities (Table 4.4, § 4.3.) so that the yield figure of 48 g per m² will still remains the most conservative estimate. Yield of plantations with densities > 16 plants per m² can not be reliably estimated on the basis of the present study. In the latter case, in the absence of real-situation figures, it is recommended to use the estimate of Toonen *et al*. (2006), which was set at 28.1 g per plant;
- assimilation lamp power density is below or above 600 W per m² (unless density of higher power lamps can be recalculated to 600 W per m²; see the second example in 6.2.1). When lamp power density deviates from 600 W per m², in the absence of real-situation figures, we recommend estimating the yield by using the figure proposed by Toonen *et al*. (2006) (28.1 g per plant);
- extremely small or large plantations. Our final recommendations are based on our third growth cycle yield figures in which 224 plants were used. Following the classification of the Belgian Federal Police, this is a (large) small-scale plantation (50 - 249 plants). However, when environmental conditions and agronomic interventions are similar to those from our third growth cycle (see chapter 4), the yield figure of 575 g per m² will be valid. Growth conditions for micro-scale (< 5 plants) or very large industrial plantations (> 1,000 plants) can

differ from those in our third cycle because of specific infrastructural or grower characteristics (e.g. sub-optimum temperature in large sheds used for industrial cannabis production or inadequate fertilization because of unprofessional hobby-growing by micro-scale growers). In case of doubt on the similarity of growth conditions in any plantation with those of the third cycle of our study, and in the absence of real-situation figures, it is recommended to use the yield figure of Toonen *et al*. (2006), which was set at 28.1 g per plant.

– there are indications of pests (such as mites) or diseases (such as *Fusarium oxysporum* or any other fungal attack). It is possible that pests and/or diseases have completely destroyed a plantation so that no commercial yield could have been obtained from the plantation.

6.2.3. Future research

To conclude with, we recommend that further research would first of all investigate whether it would be possible to skip the vegetative stage (with a 18 h light / 6 h dark regime) by subjecting rooted cuttings immediately to a flower-inducing stage (12 h light / 12 h dark regime) (see § 4.4) and what are the implications on yield and growth cycle duration.

In order to eliminate inaccuracies that might have occurred in mimicking an illicit indoor cannabis plantation at the university, it might be good to replicate the experiments in a number of confiscated indoor cannabis plantations. Obstacles include i) judiciary who usually orders dismantlement of the plantations as soon as possible after seizure; and ii) safety of the installation (e.g. electric wiring, etc.).

Future research should further take the most recent technical evolutions in indoor cannabis cultivation into account. As a result of the high profit rates associated with cannabis growing, growing techniques, as well as varieties are likely to evolve and improve continuously. As a result, it is recommended that a permanent centre of excellence in cannabis cultivation is set up (by police/government in collaboration with researchers) in which the most recent evolutions in indoor cannabis growing and their effect on cannabis yield and cannabis are continuously monitored. Factors to consider in such experiments include:

- hydroponics: were not included in the present doctoral research. Bottlenecks of hydroponics (mainly related to adequate composition and circulation of the nutrient solution) should be clearly identified prior to starting hydroponics cultivation in order to enable a confident yield estimate of hydroponics cannabis cultivation;
- most recent varieties: the experiments of the present doctoral research (2010-2011) used the then state-of-the-art cannabis strains that were obtained from Amsterdam growshops (i.e. Big Bud, Northern Lights #5 x Haze, Super Skunk, White Widow, Skunk #1, Silver Haze #9). It was found that yield differs significantly between strains. Sensi Seeds (http://sensiseeds.com/) – the main

cannabis breeder, based in Amsterdam – is nowadays advertising recently developed strains (such as Early Skunk, White Diesel, Skunk Kush or Jack Flash), in some cases promising extremely high yields (sic) (e.g. Ed Rosenthal Super Bud). However, leaflets advertising such strains never mention yield figures. Performance (yield and quality) of these new strains should be tested in standard cultivation conditions such as those we applied in the experiment reported in chapter 4.

– LED lights (instead of the classic high-pressure sodium (HPS) lights). Solid-state lighting based on the use of light-emitting diodes (LED) is potentially one of the biggest advancements in horticultural lighting in decades (Morrow, 2008). Some websites advertise LED use in indoor cannabis production as well (see e.g. http://www.prweb.com/releases/2012/6/prweb9580672.htm; last visit: 02 December 2013). In Belgium, however, only 1 of the 1,111 plantations seized in 2012, used LED lights (Benny Van Camp, Judicial Commissioner of the Directorate of Crime against Persons; personal communication). Horticultural LED lights use less than half of the power of classic HPS lamps and produce almost no heat. These characteristics can be beneficial to illicit indoor cannabis cultivation because discovery resulting from fires caused by lamp heat, or suspiciously high electricity bills is avoided. On the other hand, indoor cultivation systems with LED lights will probably require additional heating because the recommended temperature range (20 – 25 °C) is usually reached by heat released from the assimilation lights. Installation of heating systems can be complicated and will increase the variable costs of the growth cycle. However, given the expected increase of use of LED lighting in horticulture in general (Morrow, 2008), the effect of LED lights on indoor cannabis yield and quality should be tested in future research. According to some grey literature resources (internet pages), LED lighting increases Δ^9-tetrahydrocannabinol (THC) concentrations of cultivated cannabis. Future research should verify this claim.

Further research will thus enable a fine-tuned and accurate description of illicit indoor cannabis cultivation techniques and of their effect on cannabis yield and quality and will consequently form a more solid ground for prosecution of (mid- to industrial scale) indoor cannabis cultivation in Belgium, which continues to be the integral and integrated Belgian Drug Policy.

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https://www.growshoponline.nu/

https://www.icmag.com/

https://www.luminus.be/

Curriculum vitae

Personalia

Name	Wouter Vanhove
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E-mail1	Wouter.Vanhove@ugent.be
E-mail2	Wouter_Vanhove@hotmail.com
Date of birth	30 June 1977
Place of birth	Bruges
Nationality	Belgian
Marital status	Married
Children	Bonnie (° 09/09/08), Teo (° 25/05/10)

Education

Information Cycle Development Cooperation (April 2001), DGIS (currently DGOS)

Diploma: Certificate for Development Cooperation

Higher education (October 1995 - June 2000)

Institute:	Ghent University Faculty of Bio-Science Engineering Coupure Links 653 9000 Gent Belgium
MSc:	Agronomy (Option: Tropical Agronomy)
Diploma:	Bio-Engineer in Agronomy (Distinction)
Thesis:	'Generative propagation and genetic variation in the genus *Vasconcella*', with fieldwork from 1 August 1999 – 3 November 1999 in Loja (Ecuador) in the framework of the research project 'Knowledge and cultivation potential of phytogenetic resources of Southern Ecuador' (Flemish Interuniversity Council (VIIR) and the Flemish Association for Development Cooperation and Technical Relief (VVOB))

High school (September 1993 - June 1995)

Institute:	Sint-Gerolf Sint Gerolflaan 22 9880 Aalter Belgium
Study:	Mathematics – Science

Language skills

	Speak	Read	Write
Dutch (mother tongue)			
English	Excellent	Excellent	Very Good
French	Very Good	Excellent	Very Good
German	Good	Very Good	Good
Spanish	Very Good	Excellent	Very Good

Computer software skills

MS WORD	Excellent
MS EXCEL	Excellent
MS POWERPOINT	Very Good
MS ACCES	Very Good
PHOTOSHOP	Good
MS DOS	Excellent
SPSS	Excellent
QBASIC	Excellent
HTML	Good
DIVA-GIS	Very Good

Driving license

B (since 1998)

Voluntary Work

1994: Certificate ‘Animator in Youth Work’ (Mooss Vzw) obtained from the department Youth Work, Administration Social-Cultural Work of the Flemish Community

1994 – 2000: Municipal Youth Organisation, Aalter

- 2 years animator, afterwards 3 years coordinator at the municipal Speelpleinwerking;
- 1 year animator at the municipal Tienerwerking;
- organiser at the sports work group ‘Lijfgeur’;
- editor of the youth council journal ‘+VIB’;
- organiser of youth activities for the yearly happening ‘Aalter op z’n kop’;
- organiser of a youth event in the framework of the 11.11.11. (NGO)-campaign for 15-16 year-olds

Other Voluntary Work

- workshop organiser of the youth campaign ‘Greenwich’ of NCOS (NGO) (1994);
- campaigning for Vredeseilanden (NGO) (1992 - …);

– trainer in the campaign ‘Pas op! Dode hoek’ at Fietsersbond (NGO) – Antwerp (2002)

Memberships

– Parent committee at children's' school (GO De Wijze Eik, Mariakerke)
– Representative in the Parent Council at children's' school (GO De Wijze Eik, Mariakerke)
– Natuurpunt (nature conservation NGO)
– WWF
– Amnesty International
– Ethical Vegetarian Alternative (EVA)
– Family Federation

Employment record

From 01/01/06 until present Ghent University Researcher

01/06/2001 - present	Research project 'Agronomic interventions for sustainable increase of cocoa yield and quality'. Collaboration with Barry-Callebaut N.V. (Zürich / Wieze, Belgium) in Malaysia and Indonesia.
01/12/2009 – 31/05/2011	Research project 'Yield of an Illicit Indoor Cannabis Plantation', Science Policy Department of the Belgian Federal Government (BELSPO).
01/04/2009 – 30/11/2009	Organisation of and participation in a workshop on spatial analysis of genetic plant diversity within the INCO-DEV (EU-FP6) project 'Domestication And Development Of Baobab And Tamarind '(DADOBAT).
01/12/2009 – 31/03/2009	Consultancy to the project 'Opportunities offered by Fair Trade markets for Guyana’s Agricultural Diversification Export Strategy'; The Project Management Unit of the TradeCom Facility, ACP Group Program (financed by the European Development Fund).
01/01/2006 – 31/12/2008	Study of the genetic diversity and commercialisation of cherimoya (*Annona cherimola*) in the INCO-DEV (EU-FP6) project 'Promotion of Sustainable Cherimoya Production Systems through Characterisation, Use and Conservation of Local Germplasm Diversity'. Field work in Ecuador, Peru and Bolivia.

From 01/10/05 until 31/12/05 Hogeschool Gent Researcher

Development and updating of indicators for the ‘City Monitor’, a tool of the Flemish City Policy (www.thuisindestad.be/).

From 07/04/05 until 17/04/05 Ghent University (unsalaried) Researcher

Teaching of a course on ethnobotany at the University of Kisangani (UNIKIS), Democratic Republic of Congo (DRC), in the Flemish Interuniversity Council (VIIR) project 'Valorisation of Wild Edible Plants in the Kisangani Region, RDC').

From 15/08/04 until 07/03/05 Ghent University Assistant

From 15/10/03 until 30/06/04 Ghent University Researcher

Execution of the module 'Food and Agriculture' in the research project 'Elaboration of the concept of Ecological Debt' (Flemish Interuniversity Council, VIIR)

From 15/02/04 until 30/04/04 Flemish Platform on Sustainable Development (VODO) Member of Staff

Evaluation of the sustainable development policy of local authorities that have an agreement with the Flemish Community on International Cooperation.

From 16/07/03 until 31/08/03 International Centre for Reproductive Health (ICRH), Ghent University Researcher

Research project 'Science Sharing'; evaluation of relevance for development of research projects conducted at Flemish research institutes (Flemish Council for Science Policy).

From 01/07/03 until 15/07/03 Ghent University (unsalaried) Researcher

Preparation of the Own Initiatives project ''Valorisation of Wild Edible Plants in the Kisangani Region' (Flemish Interuniversity Council, VIIR), during a project formulation field trip to Kisangani, DRC.

From 24/02/03 until 15/06/03 Provincial Agricultural and Horticultural Research and Extension Centre Rumbeke – Beitem Researcher

Compilation of a scientific record on all aspects (with emphasis on pests and diseases) of leek (*Allium porrum* L.) cultivation, for *ad hoc* consultation.

From 04/09/02 until 19/12/02 Provincial Institute Flemish Ardennes Teacher

Mathematics (1^{e} grade)

From 18/06/01 until 31/12/01 Balkanactie van de Gemeenten (NGO) (Antwerp)

Economic Rehabilitation Officer in Bosnia and Hercegovina

Execution of 3 agricultural development projects in the area of Maglaj-Žepče-Zavidovići, financed by the Belgian Development Cooperation.

From 20/11/00 until 31/03/01 Institute for Agriculture and Fishery Research (ILVO) – Merelbeke Research assistant

Research project 'Biological control of root-knot nematodes (*Meloidogyne* spp.) in horticulture by the nematophagous fungus *Verticillium chlamydosporium*.

Publications

A1

Vanhove, W. and Van Damme, P. (2013). On-farm conservation of cherimoya (*Annona cherimola* Mill.) germplasm diversity. A value chain perspective. Tropical Conservation Science, 6(2), 158-180.

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Vanhove, W., Van Damme, P. & Meert, N. (2011). Factors determining yield and quality of illicit indoor cannabis (*Cannabis* spp.) production. Forensic Science International, 212(1-3), 158-163.

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