# CHAPTER 3

# IMPACT OF SUBSIDENCE ON THE PLANTS

# –

# LABORATORY MODEL

*CHAPTER 3*

# IMPACT OF SUBSIDENCE - LABORATORY MODEL

## 3.1 Introduction

The assessment of impact of subsidence on the health of vegetation has been carried out by preparing laboratory models. The subsidence profile as well as the strain on surface change as the face advances. Figure 3.1a shows the change in subsidence profile as the face advances for a typical underground coal mine. Figure 3.1b shows the strain on the surface (compressive as well as tensile) with the advancing face.

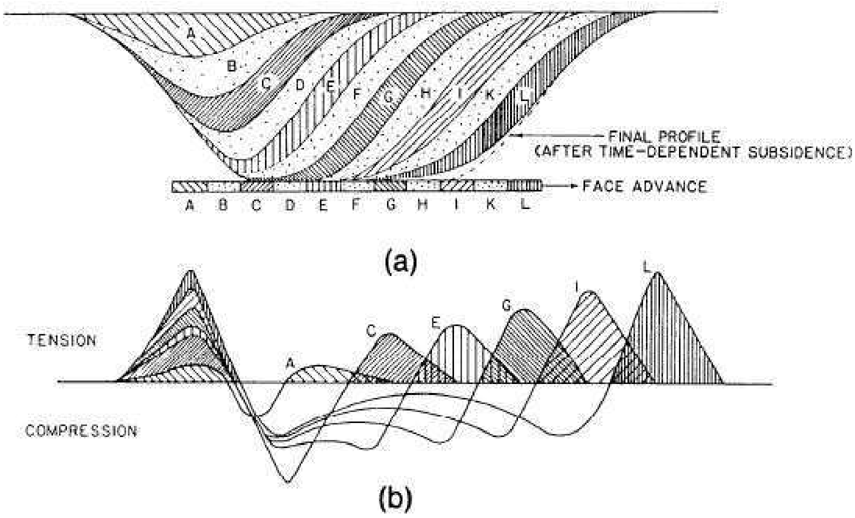


**Figure 3.1** Development of subsidence trough and strains with face advance (a) Subsidence development (b) Traveling strain curve (Rellensman and Wagner 1957; Singh 1992)

It is evident from the figure that the strain profile not only spreads to a larger area, but their magnitudes also increase with the advancement of the face. A laboratory setup was established so that the above phenomena could be studied in detail. The core issue in this setup was to study the effect of horizontal tensile strain and compressive strain resulting from subsidence on the health of plants.

The estimation of plant variables at their various growth stages is the key factor for monitoring their health. Biomass (BM), vegetation water content (VWC), chlorophyll content (CC), soil moisture (SM), leaf area index (LAI) and plant height (PH) are important crop variables to provide valuable information about the status of health condition of the plants (Gupta et al. 2016; Vishwakarma et al. 2018a, 2018b, 2020). Biomass is the total mass of living material measured over a particular area (Elhacham et al. 2020). The vegetation water content of the plant is the total water content in the plant constituents (Zarco-Tejada et al. 2003; Konings et al. 2021). It reflects the movability and transportability of the nutrients and provides important information about the translocation of plant essential matters (Vishwakarma et al. 2018a, 2018b, 2020). For the calculation of dry biomass and vegetation water content, plant density was calculated in chickpea and wolf's peach crop beds. Three quadrants of 0.5 $m^2$ area were selected at the different locations of all the crop beds. The crop samples were taken from each quadrant at each time of the growth measurements. The leaves and stalks of the samples were dried in an oven at 100 ºC for 24 hours. The samples were weighed before and after drying. The average of the samples was taken to compute the overall dry biomass and vegetation water content. The dry biomass and vegetation water content of chickpea and wolf's peach crops were calculated by using the Eq. (1) and Eq. (2), respectively (Gupta et al. 2016).

Dry biomass = Weight of dry plant sample x Plant density …………..……..……….....  (1)

VWC = (Weight of fresh plant sample - Weight of dry plant sample) x Plant density.... (2)

The chlorophyll content is an important plant variable to monitor the plant photosynthesis ability and growth status (Li et al. 2018b). Chlorophyll, a material base for photosynthesis, is the most important photosynthetic pigment (Gupta et al. 2016). The chlorophyll content is one of the most important index that reflects the photosynthetic capacity of the leaves and the state of health of the plants (Porra et al. 1989; SINGHA and Townsend 1989; Monje and Bugbee 1992; Peng et al. 1993; Gupta et al. 2016; Jiang et al. 2017). The SPAD value is the relative index of chlorophyll content in the plants. The SPAD value of the plants was measured by using an instrument SPAD-502 Plus (Cramer et al. 2001; Coste et al. 2010; Ling et al. 2011).

Gravimetric soil moisture (SM) is an important parameter that gives information about the solubility and availability of the essential nutrients to the plants (Gupta et al. 2016). The soil samples were taken at the depth of 5 cm for the gravimetric soil moisture content measurement from three different locations of the chickpea and wolf's peach crop beds. The soil samples were dried in an oven at 100 ºC for 12 hours. The soil samples were weighed before and after drying and the gravimetric soil moisture content was computed by using Eq. (3)

$$\text{SM}\ (\%) = \frac{W_{wet} - W_{dry}}{W_{dry}} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where, $W_{wet}$ and $W_{dry}$ were the weight of the soil samples before and after drying, respectively.

The leaf area index is highly related to a variety of canopy processes and directly quantifies the plant canopy structure (Peng 2000). It is defined as the ratio of the total upper leaf surface of the crops divided by the surface area of the land on which the crops are grown (Gupta et al. 2016). An instrument ACCUPAR LP-80 was used to measure leaf area index (Cohen et al. 1997; Delalieux et al. 2008; Kovacs et al. 2009). leaf area index is dimensionless; however, it is presented in the units of $m^2/m^2$.

The plant height is an important plant variable to provide the direct information about the plant type and yield potential. Thus, the estimation of plant growth variables like biomass, vegetation water content, chlorophyll content, gravimetric soil moisture, leaf area index and plant heights at its different growth stages may be used for the plant growth monitoring.

Laboratory setup was established in such a way that salient features in the field could be simulated. Tensile strain and compressive strain zones have been introduced with the help of hydraulic jacks. The magnitude of strain has also been increased periodically to simulate the increased strain with advancing face in the field.

Plants that were commonly available were carefully selected and grown in the local climatic condition. Care has been taken so that the root system of these plants is sensitive, i.e., substantial morphological changes take place due to small changes in root surroundings. Due to the space requirement and time constraints, it was not possible to grow the larger trees in the laboratory. Most of the growth behaviour mechanisms like nutrient-water uptake from the root, response to stress conditions etc. of larger plants are almost similar to that of the smaller plants. Large or small, both types of plants have almost the same principle/mechanism to meet their physiological requirements. Adopting the same principle, this study has been performed on small plants that could fit in the laboratory size model. With limited time, we could do the same work in the laboratory that could be done in the actual field condition. Further, in lab condition, the scale or size/width of the cracks may be different but to match the field condition with the lab condition, the strains produced (i.e. horizontal tensile strain and horizontal compressive strain) in the lab was similar to that of the actual field condition. Hence, the results obtained from the study on small scale (i.e. smaller plants in the laboratory) can extrapolate the same effect as in the actual field condition. Thus, the plot sizes chosen for the experiment meet the dimensionally scaled representations.

### 3.2 Model setup

Four outdoor crop beds, two of chickpea (*Cicer arietinum*) and two of wolf's peach (*Solanum lycopersicum*), of sizes ~2.5 m x 1.25 m, were specially prepared in the laboratory. Two beds were kept as flat without having any subsidence. These have been termed as control beds in subsequent discussions. One bed was prepared for chickpea and other for wolf's peach crops for control condition. The other two beds (one for chickpea and other for wolf's peach) were designed in such a way that it simulates subsidence, having horizontal tensile and compressive strain zones, named as subsidence beds. A schematic representation of control and experimental setups are shown in figures 3.2a and 3.2b, respectively. The actual laboratory model simulating the subsidence on chickpea and wolf's peach crop beds are shown in figures 3.3 and 3.4, respectively. The bed height was kept at 0.5 meter initially. The subsidence beds were fitted with hydraulic jacks (that can be lowered and raised) to introduce tensile and compressive strain zones of the desired magnitude.

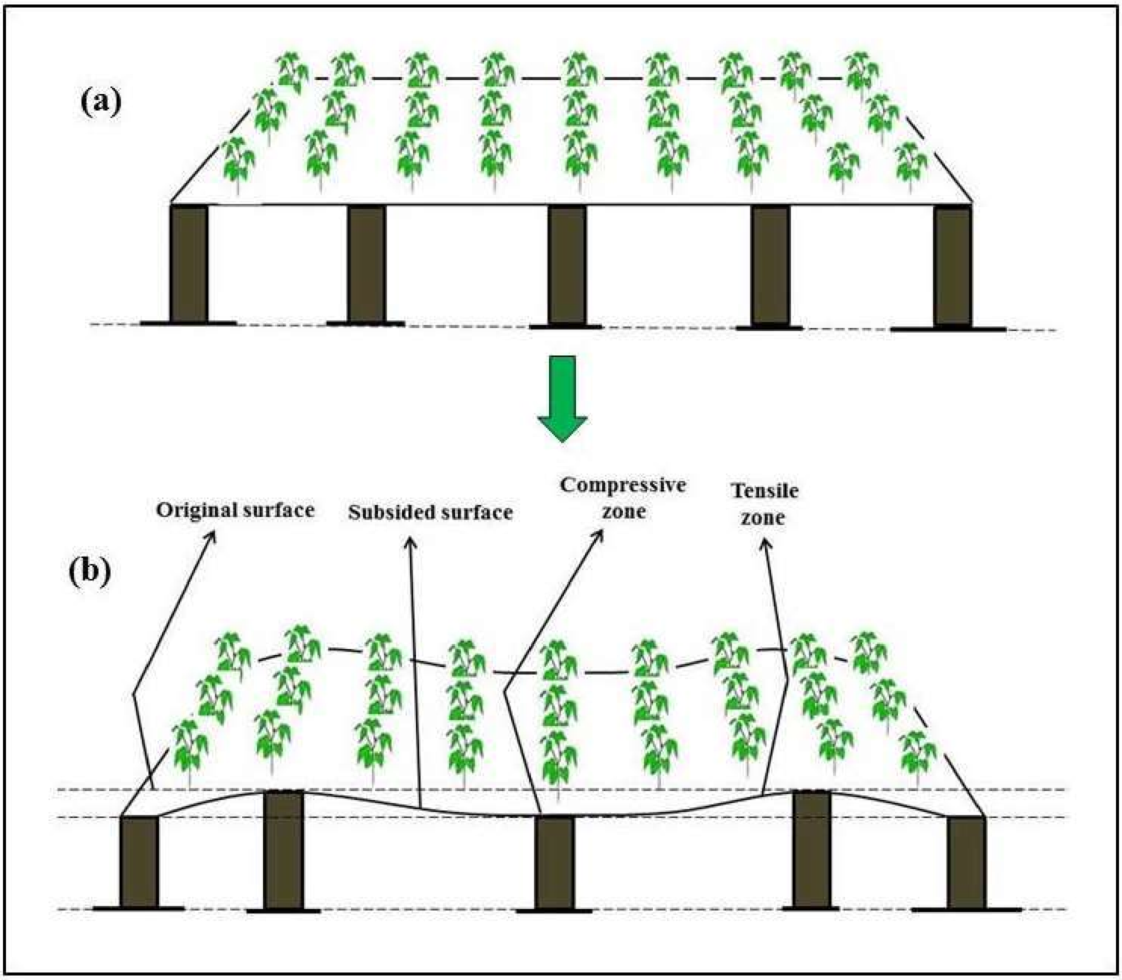


**Figure 3.2** Laboratory-based schematic model of the **a)** Control bed and **b)** Subsidence bed setups for subsidence simulation

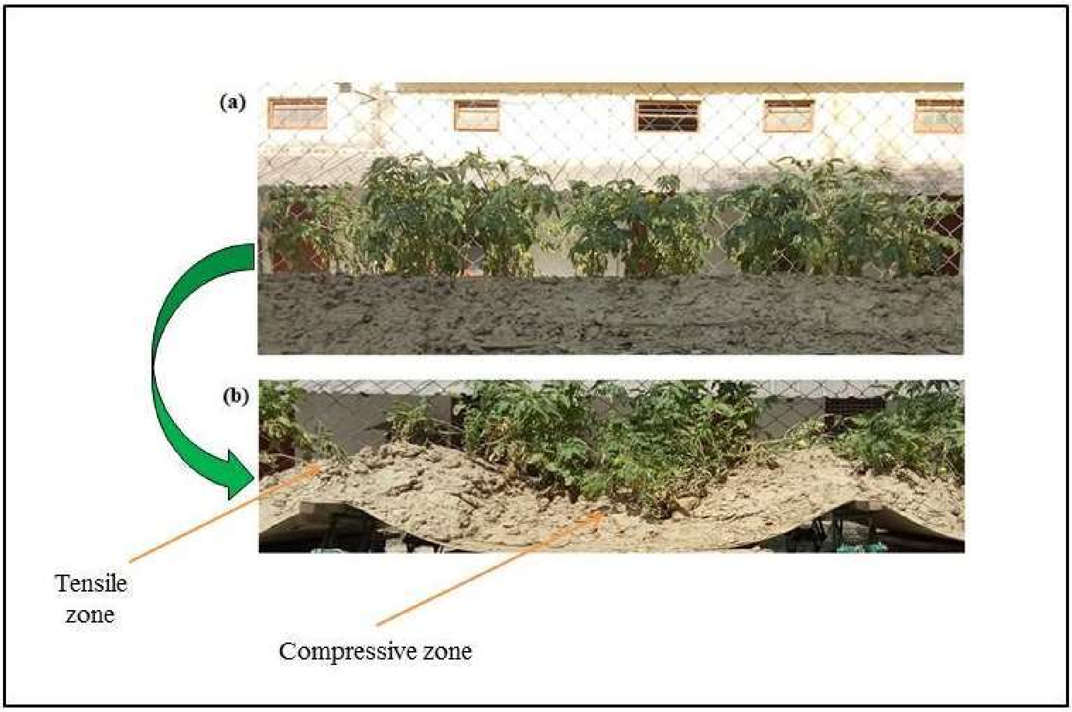


**Figure 3.3** Outdoor crop beds used for the measurement of growth variables of wolf's peach. **a** – control, **b -** experimental setup

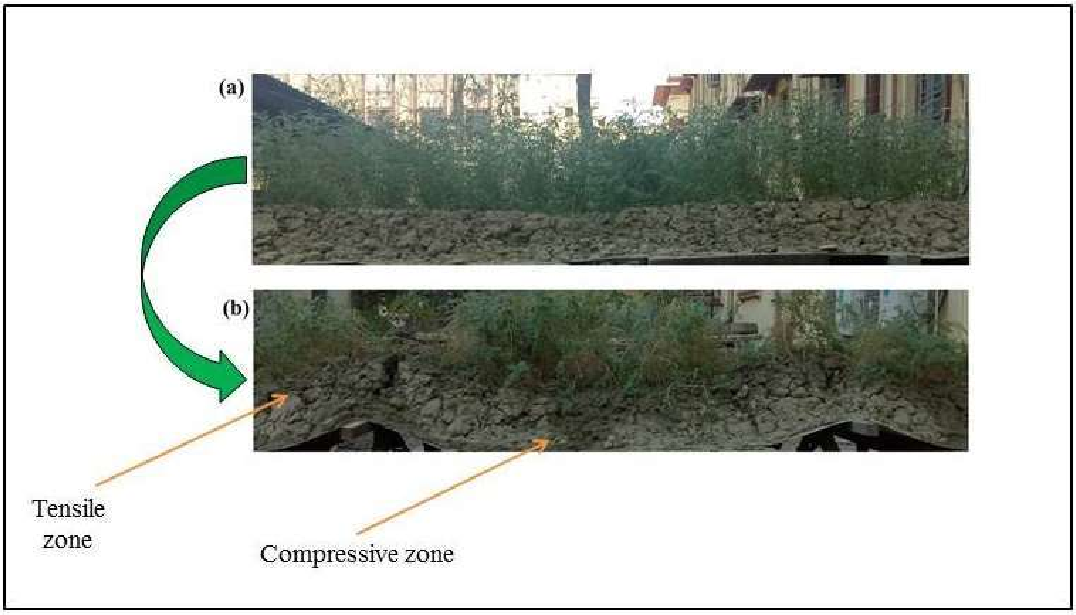


**Figure 3.4** Outdoor crop beds used for the measurement of growth variables of chickpea. **a** – control, **b -** experimental setup

Suitable soil was used for the preparation of control and subsidence beds. The soil was fertile, well-drained and high in organic matter with relatively neutral soil pH of around 6.0 to 6.8. Soils were then distributed on the four crop beds. Thus, care was taken that the type of soils used for the cultivation of plants were uniform for all of the crop beds. The thickness of the soil layer was kept around 0.5 m on each of the crop beds for the proper development of roots.

Initially, all four crop beds were kept flat. Chickpea crops were planted on two crop beds and wolf's peach crops were planted on the other two crop beds. Uniform watering has been done to maintain the uniform condition. Compressive and tensile strains have been induced with the help of hydraulic jacks in subsidence beds of chickpea and wolf's peach crops after one month of initial plant growth. The strain in the subsidence bed has been gradually increased on fortnightly basis. Data were collected after one week of inducing the subsidence (Figure 3.5). Tables 3.1 and 3.2 show the crop growth parameters of control bed of chickpea and wolf's peach crops.

**Figure 3.5** Measurements of data in the laboratory experiment

### 3.3 Results and discussion

Measurements have been taken from control beds and subsidence beds on fortnight basis with the introduction of strains by hydraulic jacks. Six parameters, i.e., BM (biomass), SM (soil moisture), VWC (vegetation water content), SPAD values, LAI (leaf area index) and PH (plant height), have been measured for control as well as for subsidence beds. The results are tabulated from Table 3.1 to Table 3.6. All the data shown in these tables represent the average of the readings of the measured growth variables. The results obtained were used to compare the growth variables' data of control and subsidence crop beds of chickpea and wolf's peach crops. The subsidence beds have compressive and tensile strain zones. The effects of compressive and tensile strains of subsidence beds on crops' growth parameters have been compared with the crops' growth parameters of control beds.

#### 3.3.1 Growth variables in control condition

Tables 3.1 and 3.2 show the results of control bed of chickpea and wolf's peach crops. It can be observed from the above tables that chickpea and wolf's peach attained maximum average height of ~44.4 cm and ~41.3 cm, respectively, at control crop bed. The maturity age of Chickpea and wolf's peach crops were found to be 91 ± 5 days and 88 ± 5 days, respectively, after the date of sowing.

All the crop variables were found to increase with the age of crops till their maturity. Maturity refers to a point in plant growth when the plant is ready to set fruit or flower. The present study has been organized in such a way that it deals with plants till their maturity only.

**Table 3.1** Data of chickpea crop with measurement dates in control condition

| Date of measurement | Dec. 26, 2017 | Jan. 09, 2018 | Jan. 23, 2018 | Feb. 06, 2018 | Feb. 20, 2018 | Mar. 6, 2018 |
|---|---|---|---|---|---|---|
| **Days after sowing** | **23** | **37** | **51** | **65** | **79** | **93** |
| **Biomass (kg/$m^2$)** | 0.44 | 0.79 | 1.23 | 1.68 | 2.34 | 2.56 |
| **LAI ($m^2/m^2$)** | 0.64 | 0.98 | 1.42 | 2.13 | 3.15 | 3.43 |
| **Chlorophyll content (SPAD value)** | 46.8 | 45.1 | 40.7 | 45.3 | 49.4 | 48.7 |
| **Plant height (cm)** | 17.8 | 22.3 | 28.7 | 34.8 | 39.2 | 44.4 |
| **Vegetation Water Content (g/$m^2$)** | 38.2 | 75.1 | 280.6 | 496.4 | 1163.8 | 1594.4 |
| **Soil Moisture (%)** | 11.1 | 11.3 | 11.5 | 10.8 | 11.7 | 12.3 |

**Table 3.2** Data of wolf's peach crop with measurement dates in control condition

| Date of measurement | Dec. 26, 2017 | Jan. 09, 2018 | Jan. 23, 2018 | Feb. 06, 2018 | Feb. 20, 2018 | Mar. 6, 2018 |
|---|---|---|---|---|---|---|
| **Days after sowing** | **23** | **37** | **51** | **65** | **79** | **93** |
| **Biomass (kg/$m^2$)** | 6.6 | 11.85 | 18.45 | 25.2 | 35.1 | 38.4 |
| **LAI ($m^2/m^2$)** | 0.67 | 1.03 | 1.49 | 2.24 | 3.31 | 3.6 |
| **Chlorophyll content (SPAD value)** | 44.59 | 42.97 | 38.78 | 43.16 | 47.07 | 46.4 |
| **Plant height (cm)** | 16.56 | 20.74 | 26.70 | 32.37 | 36.46 | 41.3 |
| **Vegetation Water Content (g/$m^2$)** | 38.58 | 75.84 | 283.38 | 501.32 | 1175.33 | 1610.2 |
| **Soil Moisture (%)** | 11.37 | 11.58 | 11.78 | 11.06 | 11.99 | 12.60 |

### 3.3.2 Growth variables in subsidence condition

The plants' growth and their health were monitored with time span and progression of subsidence. The subsidence has been induced in the subsidence crop bed with the help of hydraulic jacks by increasing the subsidence depth after the initial growth of ~23 days. The depth was progressively increased by 7 cm after 30$^{th}$, 44$^{th}$, 58$^{th}$, 72$^{nd}$ and 86$^{th}$ days after sowing. These increments produced the respective strains of 3.6 mm/m, 6.24 mm/m, 8.88 mm/m, 11.4 mm/m and 14.04 mm/m on the subsidence crop beds. Each time growth of plants was monitored after seven days of inducing subsidence and strains. Tables 3.3, 3.4, 3.5 and 3.6 show the data for subsidence conditions in both the crops. It can be observed from the tables that chickpea and wolf's peach attained maximum average height of ~43.5 cm and ~39.2 cm, respectively, at tensile strain zone and ~44.6 cm and ~42.7 cm, respectively at compressive strain zone of the subsidence crop bed.

The percentage change of growth parameters of subsidence bed has been compared with the control bed. Tables 3.3 and 3.4 show the plant growth parameters after the progression of subsidence in tensile strain zone. Tables 3.5 and 3.6 show the plant growth parameters in compressive strain zones. It can be observed that the plant growth parameters were different than the control bed parameters. This is due to strain magnitude and its nature, i.e., compressive and tensile.

Graphs of strains with six growth variables, namely biomass (BM), chlorophyll content (SPAD value), vegetation water content (VWC), soil moisture (SM), leaf area index (LAI) and plant height (PH), have been plotted. These graphs have been drawn by putting horizontal tensile strain in X-axis and percentage increase or decrease in those parameters with respect to control bed values of that parameter in Y-axis. The impact of subsidence has been assessed by comparing the growth parameter of subsided bed with control bed. The negative growth means plants have been damaged due to subsidence, while positive growth means improvement has been seen in the plants. The following discussion analyses the impact of strain on growth parameters.

**Table 3.3** Growth parameters of chickpea crop at tensile strain zone of subsidence bed

| **Dates** | **Dec. 26, 2017** | **Jan. 02, 2018** | **Jan. 09, 2018** | **Jan. 16, 2018** | **Jan. 23, 2018** | **Jan. 30, 2018** | **Feb. 06, 2018** | **Feb. 13, 2018** | **Feb. 20, 2018** | **Feb. 27, 2018** | **Mar. 6, 2018** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Events** | **Initial growth** | **Induced subsidence** | **I$^{st}$ set of data** | **Induced subsidence** | **II$^{nd}$ set of data** | **Induced subsidence** | **III$^{rd}$ set of data** | **Induced subsidence** | **IV$^{th}$ set of data** | **Induced subsidence** | **V$^{th}$ set of data** |
| **Days after sowing** | 23 | 30 | 37 | 44 | 51 | 58 | 65 | 72 | 79 | 86 | 93 |
| **Subsidence increment (cm)** | 0 | 7 | - | 7 | - | 7 | - | 7 | - | 7 | - |
| **Strain after progressive subsidence** | - | 3.6 | | 6.24 | | 8.88 | | 11.4 | | 14.04 | |
| **Biomass (kg/m$^2$)** | **0.46** | | 0.77 | | 1.22 | | 1.66 | | 2.19 | | 2..21 |
| **LAI (m$^2$/m$^2$)** | **0.68** | | 0.98 | | 1.41 | | 2.05 | | 3.11 | | 3.36 |
| **Chlorophyll content (SPAD value)** | **46.4** | | 44.8 | | 39.6 | | 44.5 | | 45.9 | | 43.9 |
| **Plant height (cm)** | **18.1** | | 22.2 | | 28.7 | | 34.1 | | 38.9 | | 43.5 |
| **Vegetation Water Content (g/m$^2$)** | **37.9** | | 74.8 | | 278.2 | | 490.6 | | 1125.5 | | 1525.4 |
| **Soil Moisture (%)** | **11.1** | | 11.2 | | 11.3 | | 10.6 | | 11.2 | | 11.2 |

**Table 3.4** Growth parameters of wolf's peach crop at tensile strain zone of subsidence bed

| **Dates** | **Dec. 26, 2017** | **Jan. 02, 2018** | **Jan. 09, 2018** | **Jan. 16, 2018** | **Jan. 23, 2018** | **Jan. 30, 2018** | **Feb. 06, 2018** | **Feb. 13, 2018** | **Feb. 20, 2018** | **Feb. 27, 2018** | **Mar. 6, 2018** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Events** | **Initial growth** | **Induced subsidence** | **I$^{st}$ set of data** | **Induced subsidence** | **II$^{nd}$ set of data** | **Induced subsidence** | **III$^{rd}$ set of data** | **Induced subsidence** | **IV$^{th}$ set of data** | **Induced subsidence** | **V$^{th}$ set of data** |
| **Days after sowing** | 23 | 30 | 37 | 44 | 51 | 58 | 65 | 72 | 79 | 86 | 93 |
| **Subsidence increment (cm)** | 0 | 7 | - | 7 | - | 7 | - | 7 | - | 7 | - |
| **Strain after progressive subsidence** | - | 3.6 | | 6.24 | | 8.88 | | 11.4 | | 14.04 | |
| **Biomass (kg/m$^2$)** | 7.1 | | 11.83 | | 18.44 | | 24.9 | | 34.7 | | 37.9 |
| **LAI (m$^2$/m$^2$)** | 0.61 | | 0.98 | | 1.41 | | 2.2 | | 3.23 | | 3.45 |
| **Chlorophyll content (SPAD value)** | 43.9 | | 42.94 | | 38.75 | | 41.9 | | 45.1 | | 42.5 |
| **Plant height (cm)** | 16.1 | | 19.52 | | 24.8 | | 30.21 | | 34.25 | | 39.2 |
| **Vegetation Water Content (g/m$^2$)** | 40.12 | | 75.61 | | 281.2 | | 484.7 | | 1135.2 | | 1535.1 |
| **Soil Moisture (%)** | 11.35 | | 11.47 | | 11.63 | | 10.4 | | 11.12 | | 11.71 |

**Table 3.5** Growth parameters of chickpea crop at compressive strain zone of subsidence bed

| Dates | Dec. 26, 2017 | Jan. 02, 2018 | Jan. 09, 2018 | Jan. 16, 2018 | Jan. 23, 2018 | Jan. 30, 2018 | Feb. 06, 2018 | Feb. 13, 2018 | Feb. 20, 2018 | Feb. 27, 2018 | Mar. 6, 2018 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Events** | **Initial growth** | **Induced subsidence** | **I$^{st}$ set of data** | **Induced subsidence** | **II$^{nd}$ set of data** | **Induced subsidence** | **III$^{rd}$ set of data** | **Induced subsidence** | **IV$^{th}$ set of data** | **Induced subsidence** | **V$^{th}$ set of data** |
| **Days after sowing** | 23 | 30 | 37 | 44 | 51 | 58 | 65 | 72 | 79 | 86 | 93 |
| **Subsidence increment (cm)** | 0 | 7 | - | 7 | - | 7 | - | 7 | - | 7 | - |
| **Strain after progressive subsidence** | - | 3.6 | | 6.24 | | 8.88 | | 11.4 | | 14.04 | |
| **Biomass (kg/m$^2$)** | **0.46** | | 0.80 | | 1.26 | | 1 .71 | | 2.41 | | 2.59 |
| **LAI (m$^2$/m$^2$)** | **0.68** | | 1.0 | | 1.43 | | 2.14 | | 3.16 | | 3.44 |
| **Chlorophyll content (SPAD value)** | **46.4** | | 45.3 | | 41.1 | | 46.2 | | 50.7 | | 49.2 |
| **Plant height (cm)** | **18.1** | | 22.4 | | 28.9 | | 35.1 | | 39.5 | | 44.6 |
| **Vegetation Water Content (g/m$^2$)** | **37.9** | | 75.2 | | 284.8 | | 500.8 | | 1170.6 | | 1598.2 |
| **Soil Moisture (%)** | **11.1** | | 11.5 | | 11.8 | | 11.1 | | 12.5 | | 12.85 |

**Table 3.6** Growth parameters of wolf's peach crop at compressive strain zone of subsidence bed

| Dates | Dec. 26, 2017 | Jan. 02, 2018 | Jan. 09, 2018 | Jan. 16, 2018 | Jan. 23, 2018 | Jan. 30, 2018 | Feb. 06, 2018 | Feb. 13, 2018 | Feb. 20, 2018 | Feb. 27, 2018 | Mar. 6, 2018 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Events** | **Initial growth** | **Induced subsidence** | **$I^{st}$ set of data** | **Induced subsidence** | **$II^{nd}$ set of data** | **Induced subsidence** | **$III^{rd}$ set of data** | **Induced subsidence** | **$IV^{th}$ set of data** | **Induced subsidence** | **$V^{th}$ set of data** |
| **Days after sowing** | 23 | 30 | 37 | 44 | 51 | 58 | 65 | 72 | 79 | 86 | 93 |
| **Subsidence increment (cm)** | 0 | 7 | - | 7 | - | 7 | - | 7 | - | 7 | - |
| **Strain after progressive subsidence** | - | 3.6 | | 6.24 | | 8.88 | | 11.4 | | 14.04 | |
| **Biomass (kg/m$^2$)** | **7.1** | | 11.86 | | 18.45 | | 25.3 | | 35.3 | | 38.51 |
| **LAI (m$^2$/m$^2$)** | **0.61** | | 1.1 | | 1.6 | | 2.26 | | 3.32 | | 3.8 |
| **Chlorophyll content (SPAD value)** | **43.9** | | 42.99 | | 39 | | 44.3 | | 48.3 | | 47.05 |
| **Plant height (cm)** | **16.1** | | 22.34 | | 27.2 | | 33.24 | | 38.12 | | 42.7 |
| **Vegetation Water Content (g/m$^2$)** | **40.12** | | 76.61 | | 288.4 | | 506.6 | | 1179.6 | | 1611.9 |
| **Soil Moisture (%)** | **11.35** | | 11.7 | | 11.9 | | 11.2 | | 12.31 | | 12.9 |

### 3.3.3 Effects of tensile strain

It is presumed that the control bed will not have any effect of subsidence as the beds are flat. The subsidence beds have tensile and compressive strain zones that are likely to affect the growth parameters compared to control beds. A parameter, i.e., the percentage change, has been taken as indicator for further discussion. The term "percentage change" has been used in subsequent discussion and defined as percentage change of parameters of subsidence beds compared to control beds.

#### 3.3.3.1 Effects of tensile strain on biomass (BM)

**Figure 3.6a** shows the percentage change in biomass of **chickpea crop** with the progress of subsidence and increase in strain values in tensile strain zone. It can be observed from the graph that the percentage change in biomass decreases with increasing tensile strain. It means that compared to control crop bed, the absolute value of biomass on subsidence crop bed decreases with increasing tensile strain. It was also observed that after 8.88 mm/m, the biomass decreases sharply with increase in tensile strain.

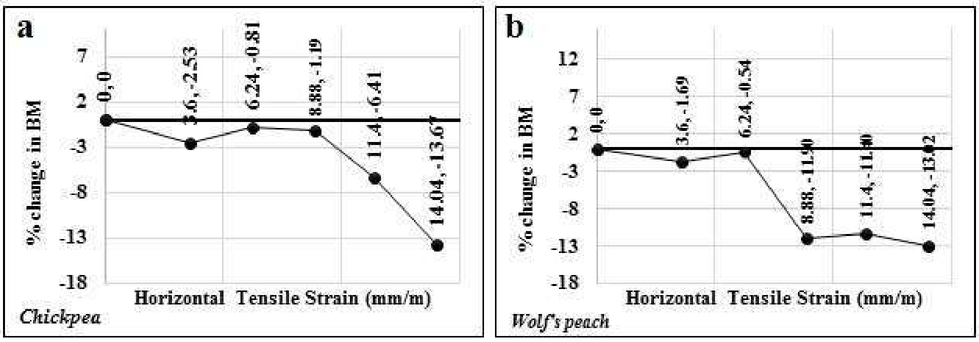


**Figure 3.6** Percentage change in biomass with increasing tensile strain in **(a)** chickpea and **(b)** wolf's peach crops

Similar study has also been carried out from wolf's peach crop to assess the effect of tensile strain on biomass. **Figure 3.6b** depicts the percentage change in biomass with increasing horizontal tensile strain. This shows the similar pattern as observed in chickpea. Percentage change in biomass decreases with increasing tensile strain. The biomass decreases sharply after 6.24 mm/m of horizontal tensile strain. Wolf's peach crop is more sensitive to horizontal tensile strain compared to chickpea.

By and large, it could be concluded that the 10 mm/m is the critical value of horizontal tensile strain for biomass beyond which the plant health will deteriorate sharply.

### 3.3.3.2 Effects of tensile strain on vegetation water content (VWC)

**Figure 3.7a** shows the percentage change of vegetation water content with increasing tensile strain values in **chickpea crop**. It can be observed that the percentage change in vegetation water content decreases with increasing tensile strain. It means that compared to control crop bed, the absolute value of vegetation water content decreases with the increase of tensile strain on subsidence crop bed. It was observed that after 8.88 mm/m tensile strain, vegetation water content decreases sharply.

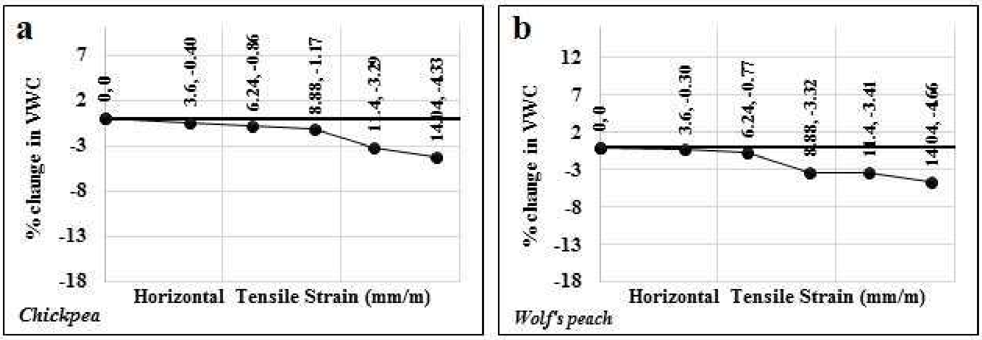


**Figure 3.7** Percentage change in vegetation water content with increasing tensile strain in **(a)** chickpea and **(b)** wolf’s peach crops

The percentage change of vegetation water content with increasing tensile strain values in **wolf’s peach crop** has been presented in **Figure 3.7b**. The percentage change of vegetation water content also decreases in **wolf’s peach** crop with increasing tensile strain. It was also observed that 6.24 mm/m was the value of tensile strain at which vegetation water content decreases sharply.

By and large, it could be concluded that approximately 10 mm/m is the critical value of horizontal tensile strain for vegetation water content beyond which the plant health will deteriorate sharply.

### 3.3.3.3 Effects of tensile strain on chlorophyll content (SPAD value)

**Figures 3.8a** and **3.8b** show the percentage change of chlorophyll content (SPAD values) with increasing tensile strain values in leaves of **chickpea** and **wolf's peach** crops, respectively. It can be observed that the percentage change in SPAD values decreases with increasing tensile strain. It was also observed that 8.88 mm/m and 6.24 mm/m were the values of tensile strain beyond which SPAD value decreases sharply in chickpea and wolf's peach crops, respectively.

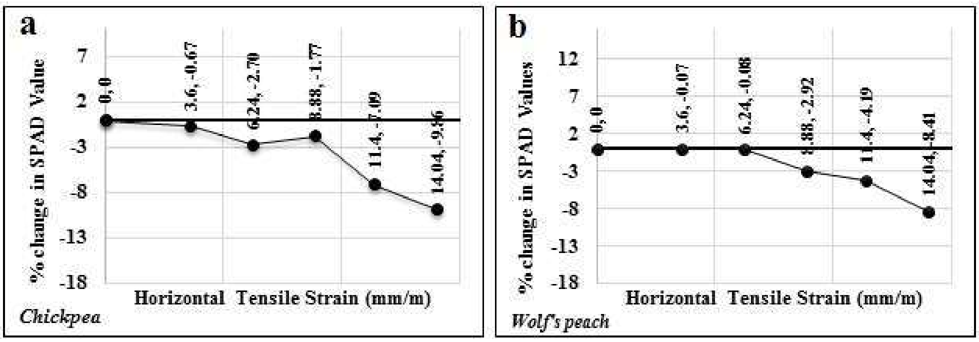


**Figure 3.8** Percentage change in chlorophyll content (SPAD value) with increasing tensile strain in **(a)** chickpea and **(b)** wolf's peach crops

It could be concluded that approximately 10 mm/m is the critical value of horizontal tensile strain for chlorophyll content, beyond which SPAD value decreases sharply and affect the plants' health.

### 3.3.3.4 Effects of tensile strain on soil moisture (SM)

Graph of percentage change in soil moisture with the progress of subsidence and increase in strain values in tensile strain zone of **chickpea crop bed** has been shown in **Figure 3.9a**. It shows that the percentage change in soil moisture decreases with the increase of tensile strain. It was observed that after 8.88 mm/m tensile strain, soil moisture decreases sharply.

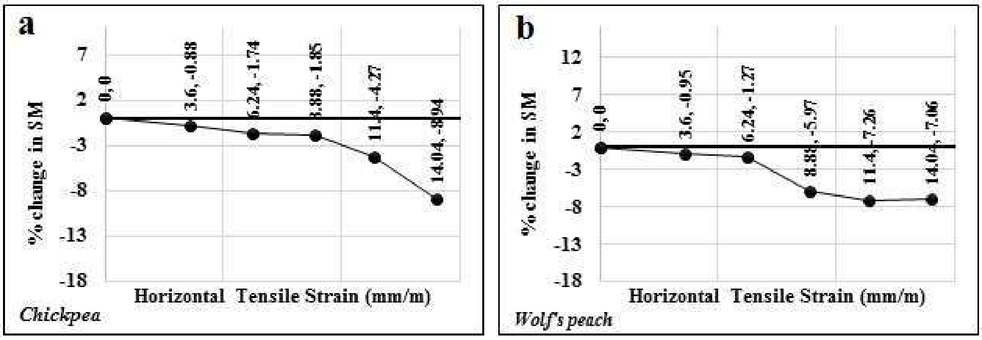


**Figure 3.9** Percentage change in soil moisture with increasing tensile strain in **(a)** chickpea and **(b)** wolf's peach crops

**Figure 3.9b** shows the percentage change in soil moisture with the progress of subsidence and increase in strain values in tensile strain zone of **wolf's peach crop bed**. It can be observed from the graph that percentage change in soil moisture decreases with increasing tensile strain. It was also observed that after 6.24 mm/m tensile strain, soil moisture decreases sharply.

By and large, it could be concluded that approximately 10 mm/m is the critical value of horizontal tensile strain for soil moisture, beyond which the plant health will deteriorate sharply.

### 3.3.3.5 Effects of tensile strain on leaf area index (LAI)

**Figure 3.10a** shows the percentage change in leaf area index of **chickpea crop** with increasing tensile strain values. It can be observed from the figure that the percentage change in leaf area index is almost constant till 6.24 mm/m of strain and after that, a fluctuating pattern has been observed.

**Figure 3.10b** shows the percentage change in leaf area index of **wolf's peach crop** with increasing tensile strain values. It can be observed from the figure that there is no pattern of leaf area index with the increasing tensile strain.

It can be concluded from this trend that there is no significant pattern on leaf area index due to horizontal tensile strain up to the maximum measured tensile strain of 14.04 mm/m.

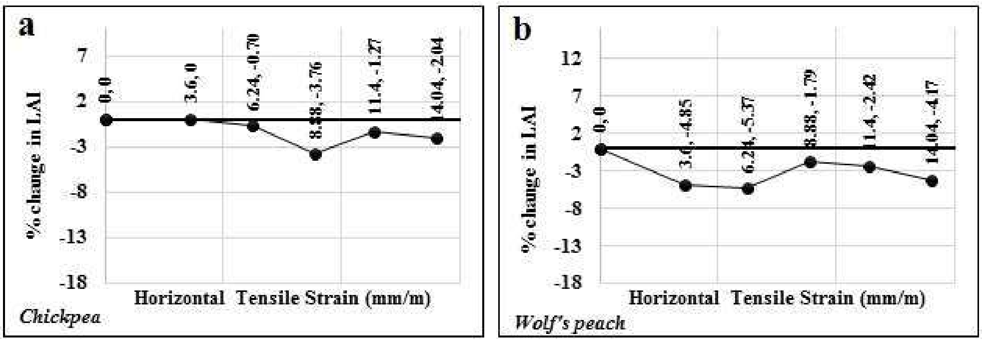


**Figure 3.10** Percentage change in leaf area index with increasing tensile strain in **(a)** chickpea and **(b)** wolf's peach crops

### 3.3.3.6 Effects of tensile strain on plant height (PH)

**Figure 3.11a** shows the percentage change of average plant heights of **chickpea crop** with increasing tensile strain values. It can be observed from the figure that the percentage change in plant heights in subsidence bed are almost same compared with control bed till 6.24 mm/m of strain and after that, a fluctuating pattern has been observed.

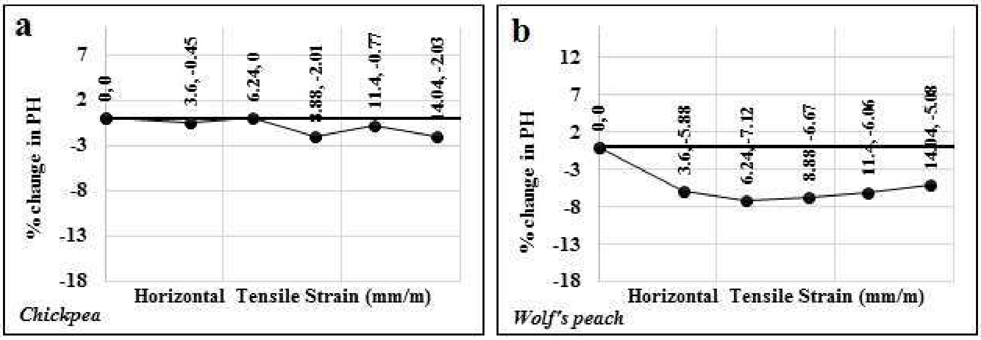


**Figure 3.11** Percentage change in plant height with increasing tensile strain in **(a)** chickpea and **(b)** wolf's peach crops

**Figure 3.11b** shows the percentage change of average plant heights of **wolf's peach crop** with increasing tensile strain values. It can be observed from the figure that the percentage change in plant heights in subsidence bed did not follow a particular pattern.

It can be concluded from the above trend that there is no significant pattern on plant height due to horizontal tensile strain up to the maximum measured tensile strain of 14.04 mm/m.

The effect of tensile strain on plant growth variables (such as biomass (BM), chlorophyll content (SPAD value), vegetation water content (VWC), soil moisture (SM), leaf area index (LAI) and plant height (PH) in the present study) can be explained in reference to linkages between water transport and mineral nutrients in the soil. Tensile strain has extremely important effects on the transport process of water and solutes in soil (Wang et al. 2016; Zhang et al. 2017a). It leads to the formation of cracks with different widths on the ground surface, which reduces the water-retaining capacity of the soil and thus decreases the water supply to the plants through the soil. During the non-raining periods, the crack increases the contact area between soil and external environment and accelerates the lateral evaporation of soil water and exacerbates the loss of water from the soil. Both the reduced water supply and the increased evaporation rate certainly lead to the reduction in soil water content. Furthermore, cracks also weaken the total water-holding capacity of the soil. The combined actions of these factors reduce soil water content to different extents (Li et al. 2011). Thus the negative change in plant growth is closely related to the migration of important nutrients with the soil water migration (Zhao et al. 2010). In the tensile affected area, many nutritional elements in the soil can more easily leak with the direct runoff along cracks during rain, which, in turn, cause the deficiency of soil nutrients, degrade soil environmental quality and affect the crop growth (Zhao et al. 2010).

### 3.3.4 Effects of compressive strain

Figures 3.12 to 3.17 show the percentage change of biomass, chlorophyll content (SPAD value), vegetation water content, soil moisture, leaf area index and plant height in chickpea crop with increasing compressive strain. The various effects of compressive strain on different parameters have been discussed below.

#### 3.3.4.1 Effects of compressive strain on biomass (BM)

**Figure 3.12a** shows the percentage change in biomass of **chickpea crop** with the progress of subsidence and increase in strain values in compressive strain zone. It can be observed from the graph that the percentage change in biomass increases to 6.24 mm/m of compressive strain. After that, a fluctuating pattern has been observed. At the maximum induced compressive strain of 14.04 mm/m, the percentage change in biomass decreases.

**Figure 3.12b** shows the percentage change in biomass of **wolf's peach crop** with the progress of subsidence and increase in strain values in compressive strain zone. It can be observed from the graph that the percentage change in biomass slightly increases at 3.6 mm/m of compressive strain. After that, a fluctuating pattern has been observed. At the maximum induced compressive strain of 14.04 mm/m, the percentage change in biomass decreases.

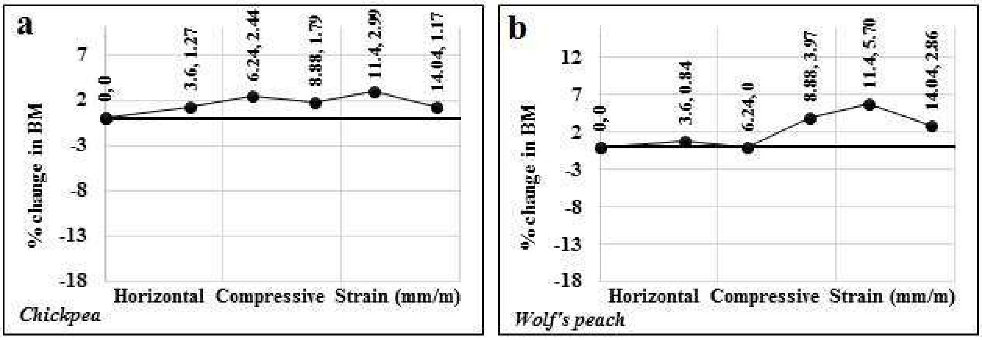


**Figure 3.12** Percentage change in biomass with increasing compressive strain in **(a)** chickpea and **(b)** wolf's peach crops

By and large, it could be concluded from the above trend that there is no significant pattern on biomass due to horizontal compressive strain up to the maximum measured compressive strain of 14.04 mm/m. It can also be concluded from the above trend of the graphs that the biomass increases slightly with the increase in soil compaction with increasing compressive strain but starts to decrease after a certain limit.

#### 3.3.4.2 Effects of compressive strain on vegetation water content (VWC)

**Figures 3.13a and 3.13b** show the percentage change in vegetation water contents of **chickpea** and **wolf's peach crops,** respectively with increasing compressive strain. It can be observed that the percentage change in vegetation water contents in both the crops increase till 6.24 mm/m of compressive strain. After that, it decreases.

By and large, it could be concluded from the above trend that the vegetation water content increases with the increase in soil compaction with increasing compressive strain but starts to decrease after a certain limit.

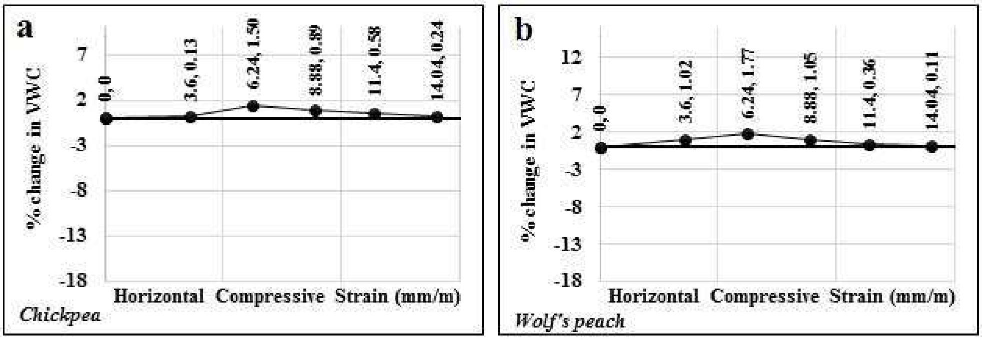


**Figure 3.13** Percentage change in vegetation water content with increasing compressive strain in **(a)** chickpea and **(b)** wolf's peach crops

**3.3.4.3 Effects of compressive strain on chlorophyll content (SPAD value)**

**Figure 3.14a** shows the percentage change of chlorophyll content (SPAD value) of **chickpea crop** with increasing compressive strain. It can be observed that the percentage change in SPAD values increases till 11.4 mm/m of compressive strain and after that, it decreases.

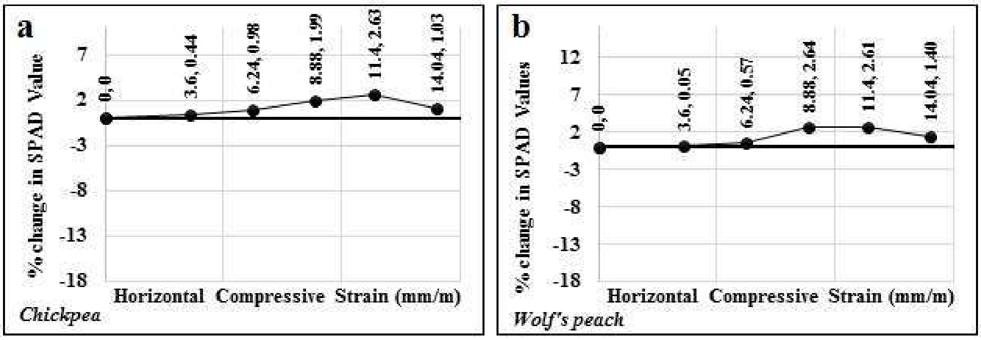


**Figure 3.14** Percentage change in chlorophyll content (SPAD value) with increasing compressive strain in **(a)** chickpea and **(b)** wolf's peach crops

**Figure 3.14b** shows the percentage change of chlorophyll content (SPAD value) of **wolf's peach crop** with increasing compressive strain. It can be observed that the percentage change in SPAD values increases till 8.88 mm/m of compressive strain and after that, it decreases.

By and large, it could be concluded from the above trend that the SPAD value increases slightly with the increase in soil compaction with increasing compressive strain but starts to decrease after a certain limit.

### 3.3.4.4 Effects of compressive strain on soil moisture (SM)

**Figures 3.15a and 3.15b** show the percentage change in soil moistures of **chickpea** and **wolf's peach crop beds,** respectively, with increasing compressive strain. It can be observed that the percentage change in soil moistures of both the crop beds increase to 11.4 mm/m of compressive strain. After that, it decreases.

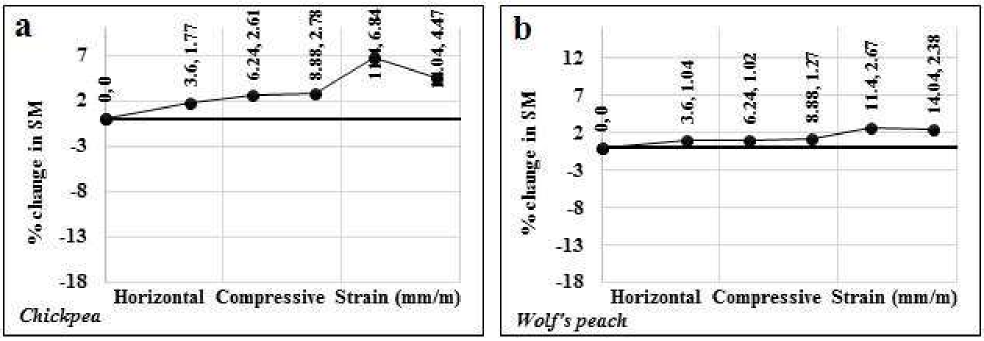


**Figure 3.15** Percentage change in soil moisture with increasing compressive strain in **(a)** chickpea and **(b)** wolf's peach crops

By and large, it could be concluded from the above trend of the graphs that the soil moisture increases with the increase in soil compaction with increasing compressive strain but starts to decrease after a certain limit.

### 3.3.4.5 Effects of compressive strain on leaf area index (LAI)

**Figure 3.16a** shows the percentage change in leaf area index of **chickpea crop** with increasing compressive strain. It can be observed that the percentage change in leaf area index increases at 3.6 mm/m of compressive strain and after that, it decreases.

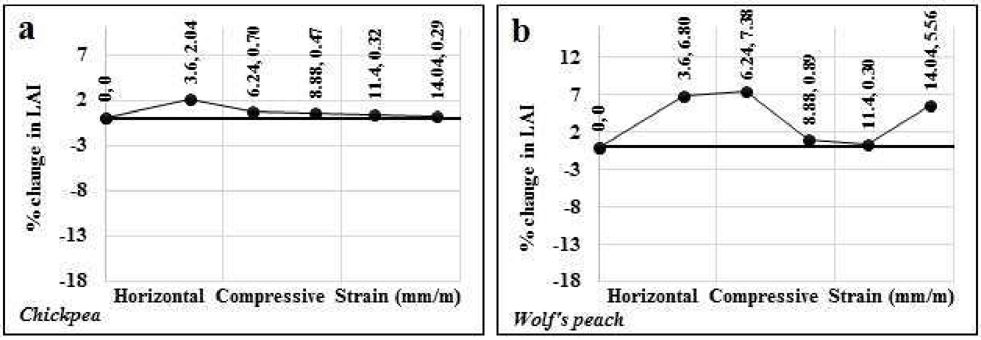


**Figure 3.16** Percentage change in leaf area index with increasing compressive strain in **(a)** chickpea and **(b)** wolf's peach crops

**Figure 3.16b** shows the percentage change in leaf area index of **wolf's peach crop** with the progress of subsidence and increase in strain values in compressive strain zone. It can be observed from the graph that the percentage change in leaf area index increases to 6.24 mm/m of compressive strain. After that, a fluctuating pattern has been observed.

By and large, it could be concluded from the above trend of the graphs that there is no significant pattern on leaf area index due to horizontal compressive strain.

### 3.3.4.6 Effects of compressive strain on plant height (PH)

**Figure 3.17a** shows the percentage change in average plant heights of **chickpea crop** with increasing compressive strain. It can be observed that the percentage change in plant heights slightly increases till 8.88 mm/m of compressive strain and after that, it decreases.

**Figure 3.17b** shows the percentage change in average plant heights of **wolf's peach crop** with increasing compressive strain. It can be observed from the graph that the percentage change in plant heights increases at 3.6 mm/m of compressive strain and after that, a fluctuating pattern has been observed.

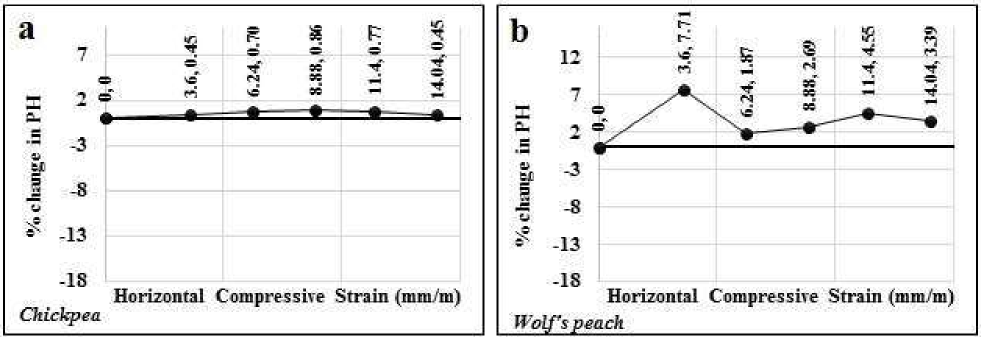


**Figure 3.17** Percentage change in plant height with increasing compressive strain in **(a)** chickpea and **(b)** wolf's peach crops

By and large, it could be concluded from the above trend of the graphs that there is no significant pattern on plant height due to horizontal compressive strain.

From the above graphs of compressive strain, it has been observed that at the maximum induced compressive strain of 14.04 mm/m, the percentage change in most of the parameters decreases. It means that compared to control crop bed, the absolute value of above parameters on subsidence crop bed increases with the lower value of compressive strain while decreases with the higher value of compressive strain. Here, a slight increase in soil compaction increases the values of growth parameters, but higher level of soil compaction decreases the values of growth parameters in both the crop. Similar results were also reported by Wang et al. (2019) and Dam et al. (2005). Wang et al. (2019) found that a moderate-level increase in soil compaction increases the growth of the soybean crops, while high-level increase in soil compaction inhibits the growth of the soybean crops. Some of the studies also supported this view and reported that the soil compaction exerts a dual effect on plant development in which moderate-level compaction positively influences plant growth (Botta et al. 2016; Ramalingam et al. 2017; Zhang et al. 2017b), while high-level compaction leads to the inhibition of plant growth (Somerville et al. 2018; Wang et al. 2013; Zhang et al. 2014b). Soil compaction affects the ratio of solids, liquids, and gases in the soil (Usowicz et al. 1996), hindering nutrient cycle (Nawaz and Trolard 2013) and hence the plant growth and development (Abu-Hamdeh 2003; Zhang et al. 2014a, 2014b; Zhang et al. 2013).

### 3.4 Concluding remark

It has been observed from the previous discussion that the tensile strain affects the plant growth parameters. Out of six studied parameters (i.e., biomass, chlorophyll content, vegetation water content, soil moisture, leaf area index and plant height), four parameters of plants (biomass, chlorophyll content, vegetation water content and soil moisture) decrease with increase in horizontal tensile strain. One can find a value of tensile strain beyond which the plant growth parameters decrease sharply. This could be termed as critical strain value. It could be concluded based on the present study that 10 mm/m is the critical horizontal tensile strain value beyond which the plant health deteriorates sharply. The health of plants improves in horizontal compressive strain. Most of the growth parameters remain same or increase slightly compared to the control condition in the effect of horizontal compressive strain.

It is important to note that all the growth parameters which have increased with the increase in horizontal compressive strain, decrease after a certain value. It implies that slight compression is better for plant growth. However, this may not be true for high horizontal compressive strain.